

Revised Social Cost of CO₂, 2010 – 2050 (in 2007 dollars per metric ton of CO₂)

Discount Rate	5.0%	3.0%	2.5%	3.0%
Year	Avg	Avg	Avg	95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

I. Purpose

The purpose of this document is to update the schedule of social cost of carbon (SCC) estimates from the 2010 interagency technical support document (TSD) (Interagency Working Group on Social Cost of Carbon 2010).¹ E.O. 13563 commits the Administration to regulatory decision making “based on the best available science.”² Additionally, the interagency group recommended in 2010 that the SCC estimates be revisited on a regular basis or as model updates that reflect the growing body of scientific and economic knowledge become available.³ New versions of the three integrated assessment models used by the U.S. government to estimate the SCC (DICE, FUND, and PAGE), are now available and have been published in the peer reviewed literature. While acknowledging the continued limitations of the approach taken by the interagency group in 2010 (documented in the original 2010 TSD), this document provides an update of the SCC estimates based on the latest peer-reviewed version of the models, replacing model versions that were developed up to ten years ago in a rapidly evolving field. It does not revisit other assumptions with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity. Improvements in the way damages are modeled are confined to those that have been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature. The agencies participating in the interagency working group continue to investigate potential improvements to the way in which economic damages associated with changes in CO₂ emissions are quantified.

Section II summarizes the major updates relevant to SCC estimation that are contained in the new versions of the integrated assessment models released since the 2010 interagency report. Section III presents the updated schedule of SCC estimates for 2010 – 2050 based on these versions of the models. Section IV provides a discussion of other model limitations and research gaps.

II. Summary of Model Updates

This section briefly summarizes changes to the most recent versions of the three integrated assessment models (IAMs) used by the interagency group in 2010. We focus on describing those model updates that are relevant to estimating the social cost of carbon, as summarized in Table 1. For example, both the DICE and PAGE models now include an explicit representation of sea level rise damages. Other revisions to PAGE include: updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages. The DICE model’s simple carbon cycle has been updated to be more consistent with a more complex climate model. The FUND model includes updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of

¹ In this document, we present all values of the SCC as the cost per metric ton of CO₂ emissions. Alternatively, one could report the SCC as the cost per metric ton of carbon emissions. The multiplier for translating between mass of CO₂ and the mass of carbon is 3.67 (the molecular weight of CO₂ divided by the molecular weight of carbon = $44/12 = 3.67$).

² http://www.whitehouse.gov/sites/default/files/omb/inforeg/eo12866/eo13563_01182011.pdf

³ See p. 1, 3, 4, 29, and 33 (Interagency Working Group on Social Cost of Carbon 2010).

methane emissions. Changes made to parts of the models that are superseded by the interagency working group’s modeling assumptions – regarding equilibrium climate sensitivity, discounting, and socioeconomic variables – are not discussed here but can be found in the references provided in each section below.

Table 1: Summary of Key Model Revisions Relevant to the Interagency SCC

IAM	Version used in 2010 Interagency Analysis	New Version	Key changes relevant to interagency SCC
DICE	2007	2010	Updated calibration of the carbon cycle model and explicit representation of sea level rise (SLR) and associated damages.
FUND	3.5 (2009)	3.8 (2012)	Updated damage functions for space heating, SLR, agricultural impacts, changes to transient response of temperature to buildup of GHG concentrations, and inclusion of indirect climate effects of methane.
PAGE	2002	2009	Explicit representation of SLR damages, revisions to damage function to ensure damages do not exceed 100% of GDP, change in regional scaling of damages, revised treatment of potential abrupt damages, and updated adaptation assumptions.

A. DICE

DICE 2010 includes a number of changes over the previous 2007 version used in the 2010 interagency report. The model changes that are relevant for the SCC estimates developed by the interagency working group include: 1) updated parameter values for the carbon cycle model, 2) an explicit representation of sea level dynamics, and 3) a re-calibrated damage function that includes an explicit representation of economic damages from sea level rise. Changes were also made to other parts of the DICE model—including the equilibrium climate sensitivity parameter, the rate of change of total factor productivity, and the elasticity of the marginal utility of consumption—but these components of DICE are superseded by the interagency working group’s assumptions and so will not be discussed here. More details on DICE2007 can be found in Nordhaus (2008) and on DICE2010 in Nordhaus (2010). The DICE2010 model and documentation is also available for download from the homepage of William Nordhaus.

Carbon Cycle Parameters

DICE uses a three-box model of carbon stocks and flows to represent the accumulation and transfer of carbon among the atmosphere, the shallow ocean and terrestrial biosphere, and the deep ocean. These parameters are “calibrated to match the carbon cycle in the Model for the Assessment of Greenhouse

Gas Induced Climate Change (MAGICC)” (Nordhaus 2008 p 44).⁴ Carbon cycle transfer coefficient values in DICE2010 are based on re-calibration of the model to match the newer 2009 version of MAGICC (Nordhaus 2010 p 2). For example, in DICE2010, in each decade, 12 percent of the carbon in the atmosphere is transferred to the shallow ocean, 4.7 percent of the carbon in the shallow ocean is transferred to the atmosphere, 94.8 percent remains in the shallow ocean, and 0.5 percent is transferred to the deep ocean. For comparison, in DICE 2007, 18.9 percent of the carbon in the atmosphere is transferred to the shallow ocean each decade, 9.7 percent of the carbon in the shallow ocean is transferred to the atmosphere, 85.3 percent remains in the shallow ocean, and 5 percent is transferred to the deep ocean.

The implication of these changes for DICE2010 is in general a weakening of the ocean as a carbon sink and therefore a higher concentration of carbon in the atmosphere than in DICE2007, for a given path of emissions. All else equal, these changes will generally increase the level of warming and therefore the SCC estimates in DICE2010 relative to those from DICE2007.

Sea Level Dynamics

A new feature of DICE2010 is an explicit representation of the dynamics of the global average sea level anomaly to be used in the updated damage function (discussed below). This section contains a brief description of the sea level rise (SLR) module; a more detailed description can be found on the model developer’s website.⁵ The average global sea level anomaly is modeled as the sum of four terms that represent contributions from: 1) thermal expansion of the oceans, 2) melting of glaciers and small ice caps, 3) melting of the Greenland ice sheet, and 4) melting of the Antarctic ice sheet.

The parameters of the four components of the SLR module are calibrated to match consensus results from the IPCC’s Fourth Assessment Report (AR4).⁶ The rise in sea level from thermal expansion in each time period (decade) is 2 percent of the difference between the sea level in the previous period and the long run equilibrium sea level, which is 0.5 meters per degree Celsius (°C) above the average global temperature in 1900. The rise in sea level from the melting of glaciers and small ice caps occurs at a rate of 0.008 meters per decade per °C above the average global temperature in 1900.

The contribution to sea level rise from melting of the Greenland ice sheet is more complex. The equilibrium contribution to SLR is 0 meters for temperature anomalies less than 1 °C and increases linearly from 0 meters to a maximum of 7.3 meters for temperature anomalies between 1 °C and 3.5 °C. The contribution to SLR in each period is proportional to the difference between the previous period’s sea level anomaly and the equilibrium sea level anomaly, where the constant of proportionality increases with the temperature anomaly in the current period.

⁴ MAGICC is a simple climate model initially developed by the U.S. National Center for Atmospheric Research that has been used heavily by the Intergovernmental Panel on Climate Change (IPCC) to emulate projections from more sophisticated state of the art earth system simulation models (Randall et al. 2007).

⁵ Documentation on the new sea level rise module of DICE is available on William Nordhaus’ website at: http://nordhaus.econ.yale.edu/documents/SLR_021910.pdf.

⁶ For a review of post-IPCC AR4 research on sea level rise, see Nicholls et al. (2011) and NAS (2011).

The contribution to SLR from the melting of the Antarctic ice sheet is -0.001 meters per decade when the temperature anomaly is below 3 °C and increases linearly between 3 °C and 6 °C to a maximum rate of 0.025 meters per decade at a temperature anomaly of 6 °C.

Re-calibrated Damage Function

Economic damages from climate change in the DICE model are represented by a fractional loss of gross economic output in each period. A portion of the remaining economic output in each period (net of climate change damages) is consumed and the remainder is invested in the physical capital stock to support future economic production, so each period's climate damages will reduce consumption in that period and in all future periods due to the lost investment. The fraction of output in each period that is lost due to climate change impacts is represented as one minus a fraction, which is one divided by a quadratic function of the temperature anomaly, producing a sigmoid ("S"-shaped) function.⁷ The loss function in DICE2010 has been expanded by adding a quadratic function of SLR to the quadratic function of temperature. In DICE2010 the temperature anomaly coefficients have been recalibrated to avoid double-counting damages from sea level rise that were implicitly included in these parameters in DICE2007.

The aggregate damages in DICE2010 are illustrated by Nordhaus (2010 p 3), who notes that "...damages in the uncontrolled (baseline) [i.e., reference] case ... in 2095 are \$12 trillion, or 2.8 percent of global output, for a global temperature increase of 3.4 °C above 1900 levels." This compares to a loss of 3.2 percent of global output at 3.4 °C in DICE2007. However, in DICE2010, annual damages are lower in most of the early periods of the modeling horizon but higher in later periods than would be calculated using the DICE2007 damage function. Specifically, the percent difference between damages in the base run of DICE2010 and those that would be calculated using the DICE2007 damage function starts at +7 percent in 2005, decreases to a low of -14 percent in 2065, then continuously increases to +20 percent by 2300 (the end of the interagency analysis time horizon), and to +160 percent by the end of the model time horizon in 2595. The large increases in the far future years of the time horizon are due to the permanence associated with damages from sea level rise, along with the assumption that the sea level is projected to continue to rise long after the global average temperature begins to decrease. The changes to the loss function generally decrease the interagency working group SCC estimates slightly given that relative increases in damages in later periods are discounted more heavily, all else equal.

B. FUND

FUND version 3.8 includes a number of changes over the previous version 3.5 (Narita et al. 2010) used in the 2010 interagency report. Documentation supporting FUND and the model's source code for all versions of the model is available from the model authors.⁸ Notable changes, due to their impact on the

⁷ The model and documentation, including formulas, are available on the author's webpage at <http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm>.

⁸ <http://www.fund-model.org/>. This report uses version 3.8 of the FUND model, which represents a modest update to the most recent version of the model to appear in the literature (version 3.7) (Anthoff and Tol, 2013). For the purpose of computing the SCC, the relevant changes (between 3.7 to 3.8) are associated with improving

SCC estimates, are adjustments to the space heating, agriculture, and sea level rise damage functions in addition to changes to the temperature response function and the inclusion of indirect effects from methane emissions.⁹ We discuss each of these in turn.

Space Heating

In FUND, the damages associated with the change in energy needs for space heating are based on the estimated impact due to one degree of warming. These baseline damages are scaled based on the forecasted temperature anomaly's deviation from the one degree benchmark and adjusted for changes in vulnerability due to economic and energy efficiency growth. In FUND 3.5, the function that scales the base year damages adjusted for vulnerability allows for the possibility that in some simulations the benefits associated with reduced heating needs may be an unbounded convex function of the temperature anomaly. In FUND 3.8, the form of the scaling has been modified to ensure that the function is everywhere concave and that there will exist an upper bound on the benefits a region may receive from reduced space heating needs. The new formulation approaches a value of two in the limit of large temperature anomalies, or in other words, assuming no decrease in vulnerability, the reduced expenditures on space heating at any level of warming will not exceed two times the reductions experienced at one degree of warming. Since the reduced need for space heating represents a benefit of climate change in the model, or a negative damage, this change will increase the estimated SCC. This update accounts for a significant portion of the difference in the expected SCC estimates reported by the two versions of the model when run probabilistically.

Sea Level Rise and Land Loss

The FUND model explicitly includes damages associated with the inundation of dry land due to sea level rise. The amount of land lost within a region is dependent upon the proportion of the coastline being protected by adequate sea walls and the amount of sea level rise. In FUND 3.5 the function defining the potential land lost in a given year due to sea level rise is linear in the rate of sea level rise for that year. This assumption implicitly assumes that all regions are well represented by a homogeneous coastline in length and a constant uniform slope moving inland. In FUND 3.8 the function defining the potential land lost has been changed to be a convex function of sea level rise, thereby assuming that the slope of the shore line increases moving inland. The effect of this change is to typically reduce the vulnerability of some regions to sea level rise based land loss, thereby lowering the expected SCC estimate.¹⁰

Agriculture

consistency with IPCC AR4 by adjusting the atmospheric lifetimes of CH₄ and N₂O and incorporating the indirect forcing effects of CH₄, along with making minor stability improvements in the sea wall construction algorithm.

⁹ The other damage sectors (water resources, space cooling, land loss, migration, ecosystems, human health, and extreme weather) were not significantly updated.

¹⁰ For stability purposes this report also uses an update to the model which assumes that regional coastal protection measures will be built to protect the most valuable land first, such that the marginal benefits of coastal protection is decreasing in the level of protection following Fankhauser (1995).

In FUND, the damages associated with the agricultural sector are measured as proportional to the sector's value. The fraction is bounded from above by one and is made up of three additive components that represent the effects from carbon fertilization, the rate of temperature change, and the level of the temperature anomaly. In both FUND 3.5 and FUND 3.8, the fraction of the sector's value lost due to the level of the temperature anomaly is modeled as a quadratic function with an intercept of zero. In FUND 3.5, the coefficients of this loss function are modeled as the ratio of two random normal variables. This specification had the potential for unintended extreme behavior as draws from the parameter in the denominator approached zero or went negative. In FUND 3.8, the coefficients are drawn directly from truncated normal distributions so that they remain in the range $[0, \infty)$ and $(-\infty, 0]$, respectively, ensuring the correct sign and eliminating the potential for divide by zero errors. The means for the new distributions are set equal to the ratio of the means from the normal distributions used in the previous version. In general the impact of this change has been to decrease the range of the distribution while spreading out the distributions' mass over the remaining range relative to the previous version. The net effect of this change on the SCC estimates is difficult to predict.

Transient Temperature Response

The temperature response model translates changes in global levels of radiative forcing into the current expected temperature anomaly. In FUND, a given year's increase in the temperature anomaly is based on a mean reverting function where the mean equals the equilibrium temperature anomaly that would eventually be reached if that year's level of radiative forcing were sustained. The rate of mean reversion defines the rate at which the transient temperature approaches the equilibrium. In FUND 3.5, the rate of temperature response is defined as a decreasing linear function of equilibrium climate sensitivity to capture the fact that the progressive heat uptake of the deep ocean causes the rate to slow at higher values of the equilibrium climate sensitivity. In FUND 3.8, the rate of temperature response has been updated to a quadratic function of the equilibrium climate sensitivity. This change reduces the sensitivity of the rate of temperature response to the level of the equilibrium climate sensitivity, a relationship first noted by Hansen et al. (1985) based on the heat uptake of the deep ocean. Therefore in FUND 3.8, the temperature response will typically be faster than in the previous version. The overall effect of this change is likely to increase estimates of the SCC as higher temperatures are reached during the timeframe analyzed and as the same damages experienced in the previous version of the model are now experienced earlier and therefore discounted less.

Methane

The IPCC AR4 notes a series of indirect effects of methane emissions, and has developed methods for proxying such effects when computing the global warming potential of methane (Forster et al. 2007). FUND 3.8 now includes the same methods for incorporating the indirect effects of methane emissions. Specifically, the average atmospheric lifetime of methane has been set to 12 years to account for the feedback of methane emissions on its own lifetime. The radiative forcing associated with atmospheric methane has also been increased by 40% to account for its net impact on ozone production and stratospheric water vapor. All else equal, the effect of this increased radiative forcing will be to increase the estimated SCC values, due to greater projected temperature anomaly.

C. PAGE

PAGE09 (Hope 2013) includes a number of changes from PAGE2002, the version used in the 2010 SCC interagency report. The changes that most directly affect the SCC estimates include: explicitly modeling the impacts from sea level rise, revisions to the damage function to ensure damages are constrained by GDP, a change in the regional scaling of damages, a revised treatment for the probability of a discontinuity within the damage function, and revised assumptions on adaptation. The model also includes revisions to the carbon cycle feedback and the calculation of regional temperatures.¹¹ More details on PAGE09 can be found in Hope (2011a, 2011b, 2011c). A description of PAGE2002 can be found in Hope (2006).

Sea Level Rise

While PAGE2002 aggregates all damages into two categories – economic and non-economic impacts -, PAGE09 adds a third explicit category: damages from sea level rise. In the previous version of the model, damages from sea level rise were subsumed by the other damage categories. In PAGE09 sea level damages increase less than linearly with sea level under the assumption that land, people, and GDP are more concentrated in low-lying shoreline areas. Damages from the economic and non-economic sector were adjusted to account for the introduction of this new category.

Revised Damage Function to Account for Saturation

In PAGE09, small initial economic and non-economic benefits (negative damages) are modeled for small temperature increases, but all regions eventually experience economic damages from climate change, where damages are the sum of additively separable polynomial functions of temperature and sea level rise. Damages transition from this polynomial function to a logistic path once they exceed a certain proportion of remaining Gross Domestic Product (GDP) to ensure that damages do not exceed 100 percent of GDP. This differs from PAGE2002, which allowed Eastern Europe to potentially experience large benefits from temperature increases, and which also did not bound the possible damages that could be experienced.

Regional Scaling Factors

As in the previous version of PAGE, the PAGE09 model calculates the damages for the European Union (EU) and then, assumes that damages for other regions are proportional based on a given scaling factor. The scaling factor in PAGE09 is based on the length of a region's coastline relative to the EU (Hope 2011b). Because of the long coastline in the EU, other regions are, on average, less vulnerable than the EU for the same sea level and temperature increase, but all regions have a positive scaling factor. PAGE2002 based its scaling factors on four studies reported in the IPCC's third assessment report, and allowed for benefits from temperature increase in Eastern Europe, smaller impacts in developed countries, and higher damages in developing countries.

¹¹ Because several changes in the PAGE model are structural (e.g., the addition of sea level rise and treatment of discontinuity), it is not possible to assess the direct impact of each change on the SCC in isolation as done for the other two models above.

Probability of a Discontinuity

In PAGE2002, the damages associated with a “discontinuity” (nonlinear extreme event) were modeled as an expected value. Specifically, a stochastic probability of a discontinuity was multiplied by the damages associated with a discontinuity to obtain an expected value, and this was added to the economic and non-economic impacts. That is, additional damages from an extreme event, such as extreme melting of the Greenland ice sheet, were multiplied by the probability of the event occurring and added to the damage estimate. In PAGE09, the probability of discontinuity is treated as a discrete event for each year in the model. The damages for each model run are estimated either with or without a discontinuity occurring, rather than as an expected value. A large-scale discontinuity becomes possible when the temperature rises beyond some threshold value between 2 and 4°C. The probability that a discontinuity will occur beyond this threshold then increases by between 10 and 30 percent for every 1°C rise in temperature beyond the threshold. If a discontinuity occurs, the EU loses an additional 5 to 25 percent of its GDP (drawn from a triangular distribution with a mean of 15 percent) in addition to other damages, and other regions lose an amount determined by the regional scaling factor. The threshold value for a possible discontinuity is lower than in PAGE2002, while the rate at which the probability of a discontinuity increases with the temperature anomaly and the damages that result from a discontinuity are both higher than in PAGE2002. The model assumes that only one discontinuity can occur and that the impact is phased in over a period of time, but once it occurs, its effect is permanent.

Adaptation

As in PAGE2002, adaptation is available to help mitigate any climate change impacts that occur. In PAGE this adaptation is the same regardless of the temperature change or sea level rise and is therefore akin to what is more commonly considered a reduction in vulnerability. It is modeled by reducing the damages by some percentage. PAGE09 assumes a smaller decrease in vulnerability than the previous version of the model and assumes that it will take longer for this change in vulnerability to be realized. In the aggregated economic sector, at the time of full implementation, this adaptation will mitigate all damages up to a temperature increase of 1°C, and for temperature anomalies between 1°C and 2°C, it will reduce damages by 15-30 percent (depending on the region). However, it takes 20 years to fully implement this adaptation. In PAGE2002, adaptation was assumed to reduce economic sector damages up to 2°C by 50-90 percent after 20 years. Beyond 2°C, no adaptation is assumed to be available to mitigate the impacts of climate change. For the non-economic sector, in PAGE09 adaptation is available to reduce 15 percent of the damages due to a temperature increase between 0°C and 2°C and is assumed to take 40 years to fully implement, instead of 25 percent of the damages over 20 years assumed in PAGE2002. Similarly, adaptation is assumed to alleviate 25-50 percent of the damages from the first 0.20 to 0.25 meters of sea level rise but is assumed to be ineffective thereafter. Hope (2011c) estimates that the less optimistic assumptions regarding the ability to offset impacts of temperature and sea level rise via adaptation increase the SCC by approximately 30 percent.

Other Noteworthy Changes

Two other changes in the model are worth noting. There is a change in the way the model accounts for decreased CO₂ absorption on land and in the ocean as temperature rises. PAGE09 introduces a linear feedback from global mean temperature to the percentage gain in the excess concentration of CO₂, capped at a maximum level. In PAGE2002, an additional amount was added to the CO₂ emissions each period to account for a decrease in ocean absorption and a loss of soil carbon. Also updated is the method by which the average global and annual temperature anomaly is downscaled to determine annual average regional temperature anomalies to be used in the regional damage functions. In PAGE2002, the scaling was determined solely based on regional difference in emissions of sulfate aerosols. In PAGE09, this regional temperature anomaly is further adjusted using an additive factor that is based on the average absolute latitude of a region relative to the area weighted average absolute latitude of the Earth's landmass, to capture relatively greater changes in temperature forecast to be experienced at higher latitudes.

III. Revised SCC Estimates

The updated versions of the three integrated assessment models were run using the same methodology detailed in the 2010 TSD (Interagency Working Group on Social Cost of Carbon 2010). The approach along with the inputs for the socioeconomic emissions scenarios, equilibrium climate sensitivity distribution, and discount rate remains the same. This includes the five reference scenarios based on the EMF-22 modeling exercise, the Roe and Baker equilibrium climate sensitivity distribution calibrated to the IPCC AR4, and three constant discount rates of 2.5, 3, and 5 percent.

As was previously the case, the use of three models, three discount rates, and five scenarios produces 45 separate distributions for the global SCC. The approach laid out in the 2010 TSD applied equal weight to each model and socioeconomic scenario in order to reduce the dimensionality down to three separate distributions representative of the three discount rates. The interagency group selected four values from these distributions for use in regulatory analysis. Three values are based on the average SCC across models and socio-economic-emissions scenarios at the 2.5, 3, and 5 percent discount rates, respectively. The fourth value was chosen to represent the higher-than-expected economic impacts from climate change further out in the tails of the SCC distribution. For this purpose, the 95th percentile of the SCC estimates at a 3 percent discount rate was chosen. (A detailed set of percentiles by model and scenario combination and additional summary statistics for the 2020 values is available in the Appendix.) As noted in the 2010 TSD, "the 3 percent discount rate is the central value, and so the central value that emerges is the average SCC across models at the 3 percent discount rate" (Interagency Working Group on Social Cost of Carbon 2010, p. 25). However, for purposes of capturing the uncertainties involved in regulatory impact analysis, the interagency group emphasizes the importance and value of including all four SCC values.

Table 2 shows the four selected SCC estimates in five year increments from 2010 to 2050. Values for 2010, 2020, 2030, 2040, and 2050 are calculated by first combining all outputs (10,000 estimates per

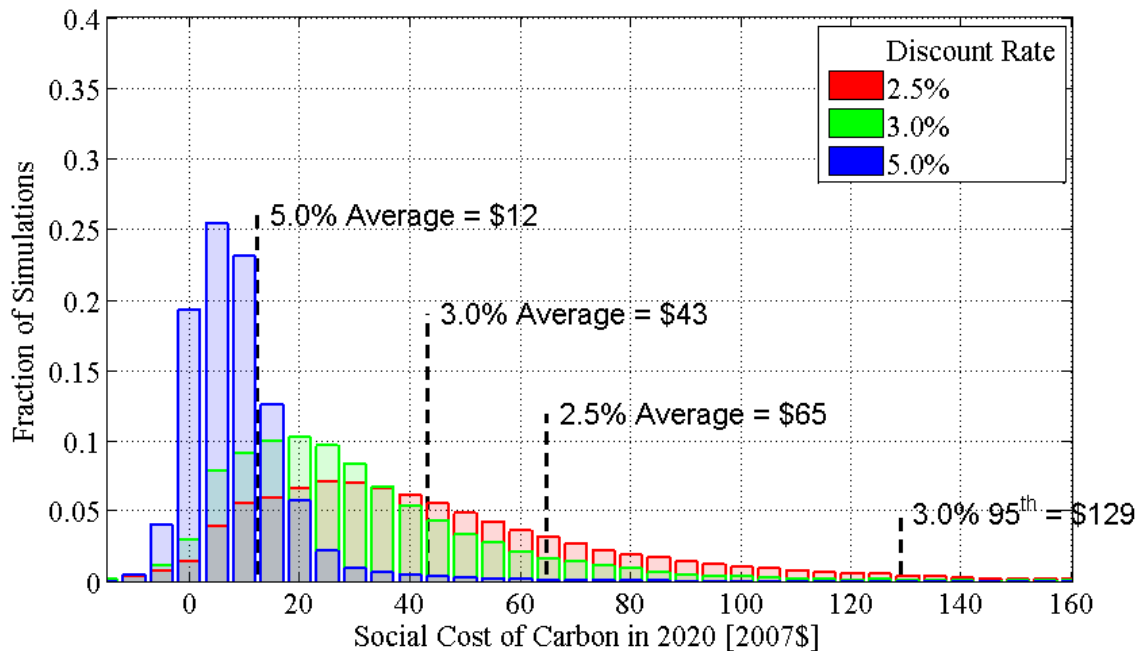
model run) from all scenarios and models for a given discount rate. Values for the years in between are calculated using linear interpolation. The full set of revised annual SCC estimates between 2010 and 2050 is reported in the Appendix.

Table 2: Revised Social Cost of CO₂, 2010 – 2050 (in 2007 dollars per metric ton of CO₂)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

The SCC estimates using the updated versions of the models are higher than those reported in the 2010 TSD due to the changes to the models outlined in the previous section. By way of comparison, the 2020 SCC estimates reported in the original TSD were \$7, \$26, \$42 and \$81 (2007\$) (Interagency Working Group on Social Cost of Carbon 2010). Figure 1 illustrates where the four SCC values for 2020 fall within the full distribution for each discount rate based on the combined set of runs for each model and scenario (150,000 estimates in total for each discount rate). In general, the distributions are skewed to the right and have long tails. The Figure also shows that the lower the discount rate, the longer the right tail of the distribution.

Figure 1: Distribution of SCC Estimates for 2020 (in 2007\$ per metric ton CO₂)



As was the case in the 2010 TSD, the SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change. The approach taken by the interagency group is to compute the cost of a marginal ton emitted in the future by running the models for a set of perturbation years out to 2050. Table 3 illustrates how the growth rate for these four SCC estimates varies over time.

Table 3: Average Annual Growth Rates of SCC Estimates between 2010 and 2050

Average Annual Growth Rate (%)	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010-2020	1.2%	3.2%	2.4%	4.3%
2020-2030	3.4%	2.1%	1.7%	2.4%
2030-2040	3.0%	1.8%	1.5%	2.0%
2040-2050	2.6%	1.6%	1.3%	1.5%

The future monetized value of emission reductions in each year (the SCC in year t multiplied by the change in emissions in year t) must be discounted to the present to determine its total net present value for use in regulatory analysis. As previously discussed in the 2010 TSD, damages from future emissions should be discounted at the same rate as that used to calculate the SCC estimates themselves to ensure internal consistency – i.e., future damages from climate change, whether they result from emissions today or emissions in a later year, should be discounted using the same rate.

Under current OMB guidance contained in Circular A-4, analysis of economically significant proposed and final regulations from the domestic perspective is required, while analysis from the international perspective is optional. However, the climate change problem is highly unusual in at least two respects. First, it involves a global externality: emissions of most greenhouse gases contribute to damages around

the world even when they are emitted in the United States. Consequently, to address the global nature of the problem, the SCC must incorporate the full (global) damages caused by GHG emissions. Second, climate change presents a problem that the United States alone cannot solve. Even if the United States were to reduce its greenhouse gas emissions to zero, that step would be far from enough to avoid substantial climate change. Other countries would also need to take action to reduce emissions if significant changes in the global climate are to be avoided. Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions and in encouraging other nations, including emerging major economies, to take significant steps to reduce emissions. When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable. For additional discussion, see the 2010 TSD.

IV. Other Model Limitations and Research Gaps

The 2010 interagency SCC TSD discusses a number of important limitations for which additional research is needed. In particular, the document highlights the need to improve the quantification of both non-catastrophic and catastrophic damages, the treatment of adaptation and technological change, and the way in which inter-regional and inter-sectoral linkages are modeled. While the new version of the models discussed above offer some improvements in these areas, further work remains warranted. The 2010 TSD also discusses the need to more carefully assess the implications of risk aversion for SCC estimation as well as the inability to perfectly substitute between climate and non-climate goods at higher temperature increases, both of which have implications for the discount rate used. EPA, DOE, and other agencies continue to engage in research on modeling and valuation of climate impacts that can potentially improve SCC estimation in the future.

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Appendix

Table A1: Annual SCC Values: 2010-2050 (2007\$/metric ton CO₂)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2011	11	34	54	94
2012	11	35	55	98
2013	11	36	56	102
2014	11	37	57	106
2015	12	38	58	109
2016	12	39	60	113
2017	12	40	61	117
2018	12	41	62	121
2019	12	42	63	125
2020	12	43	65	129
2021	13	44	66	132
2022	13	45	67	135
2023	13	46	68	138
2024	14	47	69	141
2025	14	48	70	144
2026	15	49	71	147
2027	15	49	72	150
2028	15	50	73	153
2029	16	51	74	156
2030	16	52	76	159
2031	17	53	77	163
2032	17	54	78	166
2033	18	55	79	169
2034	18	56	80	172
2035	19	57	81	176
2036	19	58	82	179
2037	20	59	84	182
2038	20	60	85	185
2039	21	61	86	188
2040	21	62	87	192
2041	22	63	88	195
2042	22	64	89	198
2043	23	65	90	200
2044	23	65	91	203
2045	24	66	92	206
2046	24	67	94	209
2047	25	68	95	212
2048	25	69	96	215
2049	26	70	97	218
2050	27	71	98	221

Table A2: 2020 Global SCC Estimates at 2.5 Percent Discount Rate (2007\$/metric ton CO₂)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95 th	99th
Scenario ¹²	PAGE									
IMAGE	6	11	15	27	58	129	139	327	515	991
MERGE	4	6	9	16	34	78	82	196	317	649
MESSAGE	4	8	11	20	42	108	107	278	483	918
MiniCAM Base	5	9	12	22	47	107	113	266	431	872
5th Scenario	2	4	6	11	25	85	68	200	387	955

Scenario	DICE									
IMAGE	25	31	37	47	64	72	92	123	139	161
MERGE	14	18	20	26	36	40	50	65	74	85
MESSAGE	20	24	28	37	51	58	71	95	109	221
MiniCAM Base	20	25	29	38	53	61	76	102	117	135
5th Scenario	17	22	25	33	45	52	65	91	106	126

Scenario	FUND									
IMAGE	-17	-1	5	17	34	44	59	90	113	176
MERGE	-7	2	7	16	30	35	49	72	91	146
MESSAGE	-19	-4	2	12	27	32	46	70	87	135
MiniCAM Base	-9	1	8	18	35	45	59	87	108	172
5th Scenario	-30	-12	-5	6	19	24	35	57	72	108

Table A3: 2020 Global SCC Estimates at 3 Percent Discount Rate (2007\$/metric ton CO₂)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	4	7	10	18	38	91	95	238	385	727
MERGE	2	4	6	11	23	56	58	142	232	481
MESSAGE	3	5	7	13	29	75	74	197	330	641
MiniCAM Base	3	5	8	14	30	73	75	184	300	623
5th Scenario	1	3	4	7	17	58	48	136	264	660

Scenario	DICE									
IMAGE	16	21	24	32	43	48	60	79	90	102
MERGE	10	13	15	19	25	28	35	44	50	58
MESSAGE	14	18	20	26	35	40	49	64	73	83
MiniCAM Base	13	17	20	26	35	39	49	65	73	85
5th Scenario	12	15	17	22	30	34	43	58	67	79

Scenario	FUND									
IMAGE	-14	-3	1	9	20	25	35	54	69	111
MERGE	-8	-1	3	9	18	22	31	47	60	97
MESSAGE	-16	-5	-1	6	16	18	28	43	55	88
MiniCAM Base	-9	-1	3	10	21	27	35	53	67	107
5th Scenario	-22	-10	-5	2	10	13	20	33	42	63

¹² See 2010 TSD for a description of these scenarios.

Table A4: 2020 Global SCC Estimates at 5 Percent Discount Rate (2007\$/metric ton CO₂)

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	1	2	2	5	10	28	27	71	123	244
MERGE	1	1	2	3	7	17	17	45	75	153
MESSAGE	1	1	2	4	9	24	22	60	106	216
MiniCAM Base	1	1	2	3	8	21	21	54	94	190
5th Scenario	0	1	1	2	5	18	14	41	78	208

Scenario	DICE									
IMAGE	6	8	9	11	14	15	18	22	25	27
MERGE	4	5	6	7	9	10	12	15	16	18
MESSAGE	6	7	8	10	12	13	16	20	22	25
MiniCAM Base	5	6	7	8	11	12	14	18	20	22
5th Scenario	5	6	6	8	10	11	14	17	19	21

Scenario	FUND									
IMAGE	-9	-5	-3	-1	2	3	6	11	15	25
MERGE	-6	-3	-2	0	3	4	7	12	16	27
MESSAGE	-10	-6	-4	-1	2	2	5	9	13	23
MiniCAM Base	-7	-3	-2	0	3	4	7	11	15	26
5th Scenario	-11	-7	-5	-2	0	0	3	6	8	14

Table A5: Additional Summary Statistics of 2020 Global SCC Estimates

Discount rate:	5.0%				3.0%				2.5%			
Statistic:	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis	Mean	Variance	Skewness	Kurtosis
DICE	12	26	2	15	38	409	3	24	57	1097	3	30
PAGE	22	1616	5	32	71	14953	4	22	101	29312	4	23
FUND	3	560	-170	35222	21	22487	-85	18842	36	68055	-46	13105

Exhibit 12



July 2014

REGULATORY IMPACT ANALYSIS

Development of Social Cost of Carbon Estimates

Why GAO Did This Study

Executive Order 12866 directs federal agencies to assess the economic effects of their proposed significant regulatory actions, including a determination that a regulation's benefits justify the costs. In 2008, a federal appeals court directed DOT to update a regulatory impact analysis with an estimate of the social cost of carbon—the dollar value of the net effects (damages and benefits) of an increase in emissions of carbon dioxide, a greenhouse gas.

In 2009, the Interagency Working Group on Social Cost of Carbon was convened to develop estimates for use governmentwide, and it issued final estimates in its 2010 Technical Support Document. In 2013, the group issued revised estimates that were about 50 percent higher than the 2010 estimates, which raised public interest.

GAO was asked to review the working group's development of social cost of carbon estimates. This report describes the participating entities and processes and methods they used to develop the 2010 and 2013 estimates. GAO reviewed executive orders, OMB guidance, the Technical Support Document, its 2013 update, and other key documents. GAO interviewed officials who participated in the working group on behalf of the EOP offices and agencies involved. GAO did not evaluate the quality of the working group's approach.

GAO is making no recommendations in this report. Of seven agencies, OMB and Treasury provided written or oral comments and generally agreed with the findings in this report. Other agencies provided technical comments only or had no comments.

View [GAO-14-663](#). For more information, contact J. Alfredo Gómez at (202) 512-3841 or gomezj@gao.gov.

July 2014

REGULATORY IMPACT ANALYSIS

Development of Social Cost of Carbon Estimates

What GAO Found

To develop the 2010 and 2013 social cost of carbon estimates, the Office of Management and Budget (OMB) and Council of Economic Advisers convened and led an informal interagency working group in which four other offices from the Executive Office of the President (EOP) and six federal agencies participated. Participating agencies were the Environmental Protection Agency (EPA) and the Departments of Agriculture, Commerce, Energy, Transportation (DOT), and the Treasury. According to several working group participants, the working group included relevant subject-matter experts and the agencies likely to use the estimates in future rulemakings. According to OMB staff, there is no single approach for convening informal interagency working groups and no requirement that this type of working group should document its activities or proceedings. However, OMB and EPA participants stated that the working group documented all major issues discussed in the Technical Support Document, which is consistent with federal standards for internal control. According to the Technical Support Document and participants GAO interviewed, the working group's processes and methods reflected the following three principles:

- **Used consensus-based decision making.** The working group used a consensus-based approach for making key decisions in developing the 2010 and 2013 estimates. Participants generally stated that they were satisfied that the Technical Support Document addressed individual comments on draft versions and reflected the overall consensus of the working group.
- **Relied on existing academic literature and models.** The working group relied largely on existing academic literature and models to develop its estimates. Specifically, the working group used three prevalent academic models that integrate climate and economic data to estimate future economic effects from climate change. The group agreed on three modeling inputs reflecting the wide uncertainty in the academic literature, including discount rates. Once the group reached agreement, EPA officials—sometimes with the assistance of the model developers—calculated the estimates. All other model assumptions and features were unchanged by the working group, which weighted each model equally to calculate estimates. After the academic models were updated to reflect new scientific information, such as in sea level rise and associated damages, the working group used the updated models to revise its estimates in 2013, resulting in higher estimates.
- **Took steps to disclose limitations and incorporate new information.** The Technical Support Document discloses several limitations of the estimates and areas that the working group identified as being in need of additional research. It also sets a goal of revisiting the estimates when substantially updated models become available. Since 2008, agencies have published dozens of regulatory actions for public comment that use various social cost of carbon estimates in regulatory analyses and, according to working group participants, agencies received many comments on the estimates throughout this process. Several participants told GAO that the working group decided to revise the estimates in 2013 after a number of public comments encouraged revisions because the models used to develop the 2010 estimates had been updated and used in peer-reviewed academic literature.

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Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
DICE	Dynamic Integrated Climate and Economy
DOT	Department of Transportation
EOP	Executive Office of the President
EPA	Environmental Protection Agency
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution
NHTSA	National Highway Traffic Safety Administration
OMB	Office of Management and Budget
PAGE	Policy Analysis of the Greenhouse Effect

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July 24, 2014

The Honorable David Vitter
Ranking Member
Committee on Environment and Public Works
United States Senate

The Honorable Tim Murphy
Chairman
Subcommittee on Oversight and Investigations
Committee on Energy and Commerce
House of Representatives

The Honorable John Culberson
House of Representatives

The Honorable Duncan Hunter
House of Representatives

To encourage a regulatory system that protects and improves health, safety, the environment, and the economy, without imposing unreasonable costs on society, federal agencies are required to assess the economic effects of proposed significant regulatory actions. Agencies can use regulatory impact analysis to assess whether a proposed regulation's benefits justify the costs. For example, regulations aimed at benefiting society by decreasing health risks associated with air pollution may require regulated entities, such as power plants, to incur costs for installing pollution control technologies. According to Environmental Protection Agency (EPA) officials, beginning in 2008, some agencies' regulatory impact analyses incorporated estimates of the social cost of carbon,¹ which agencies use to value the net effects of reducing or

¹The social cost of carbon (measured in dollars per metric ton of carbon dioxide) is the monetized net effects (damages and benefits) associated with an incremental increase in carbon emissions in a given year. Estimates of the social cost of carbon depend on the data and the models used to calculate them and can include a wide range of damage categories, such as projected changes in net agricultural productivity, human health, and property damages from increased flood risk due to increased carbon emissions. Monetization is the process of estimating the dollar value of benefits and costs.

increasing carbon dioxide emissions.² In 2009, in part because agencies used varying estimates of the social cost of carbon, the Executive Office of the President's (EOP) Office of Management and Budget (OMB) and Council of Economic Advisers convened an interagency working group to develop social cost of carbon estimates for federal agencies to use in their regulatory impact analyses. The working group finalized its estimates in 2010 and included them in a document—called the Technical Support Document—that also provides guidance for agencies on using the estimates.³ In May 2013, the working group issued an update to the Technical Support Document that included revised estimates of the social cost of carbon.⁴ These 2013 estimates of the social cost of carbon were approximately 50 percent higher than the 2010 estimates, which raised public interest.

You asked us to review the interagency working group's development of social cost of carbon estimates. This report describes the approach used, including participating entities and processes and methods, to develop the 2010 and 2013 social cost of carbon estimates for regulatory impact analysis.

To address this objective, we reviewed pertinent requirements and guidance, including executive orders and OMB guidance; the Technical Support Document and its 2013 update; published materials and presentations by working group participants on the development of the social cost of carbon estimates; and related GAO reports. We interviewed current and former federal officials or staff who participated in the working group on behalf of the EOP offices and agencies named in the Technical

²Carbon dioxide is a greenhouse gas recognized as a major contributor to climate change. Concentrations of greenhouse gases—including carbon dioxide, methane, nitrous oxide, and synthetic chemicals such as fluorinated gases—trap heat in the atmosphere and prevent it from returning to space.

³Interagency Working Group on Social Cost of Carbon, United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866* (Washington, D.C.: February 2010).

⁴Interagency Working Group on Social Cost of Carbon, United States Government, *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866* (Washington, D.C.: May 2013). This document was reissued with minor technical corrections in November 2013.

Support Document.⁵ We identified these participants by contacting all of the agencies and OMB and then following up with additional individuals identified during our discussions with them. Through this process, we interviewed over 20 individuals who participated in the working group to develop the estimates in the Technical Support Document or its 2013 update, or both. We also corresponded with researchers who developed key academic materials the working group used. Our review describes the approach the working group used to develop estimates of the social cost of carbon; evaluating the quality of the approach is outside the scope of this review.

We conducted this performance audit from November 2013 to July 2014 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

Executive Order 12866 directs federal agencies to assess the potential costs and benefits of their significant regulatory actions, consisting of several categories of regulatory actions, including those likely to result in a rule that may have an annual effect on the economy of \$100 million or more or that have a material adverse effect on the economy; a sector of the economy; productivity; competition; jobs; the environment; public health or safety; or state, local, or tribal governments or communities.⁶ Under the executive order, for regulatory actions expected to meet this

⁵According to the Technical Support Document, the working group consisted of participants from the Council of Economic Advisers, Council on Environmental Quality, EPA, National Economic Council, Office of Energy and Climate Change, OMB, Office of Science and Technology Policy, and the Departments of Agriculture, Commerce, Energy, Transportation, and the Treasury. In March 2011, the Office of Energy and Climate Change joined the Domestic Policy Council.

⁶Exec. Order No. 12866, 58 Fed. Reg. 51,735 (Sept. 30, 1993). Other significant regulatory actions include those that are likely to result in a rule that may create a serious inconsistency or otherwise interfere with an action taken or planned by another agency; materially alter the budgetary impact of entitlements, grants, user fees, or loan programs or the rights and obligations of recipients thereof; or raise novel legal or policy issues arising out of legal mandates, the President's priorities, or the principles set forth in Executive Order 12866.

threshold, or economically significant regulatory actions, agencies must also assess costs and benefits of reasonably feasible alternatives and explain why the planned regulatory action is preferable to the identified alternatives. For each significant regulatory action, the agency is to develop the proposed regulation and associated regulatory impact analysis and submit them to OMB for formal review. After OMB concludes its review, the agency is to publish the proposed rule in the *Federal Register* for public comment. The agency is to issue a document summarizing its consideration of the public comments and, if appropriate, modify the proposed rule in response to the comments. This phase of regulatory development may also include further internal and external review. For significant regulatory actions, the agency is to submit the final regulatory impact analysis and regulation to OMB for review before it publishes the final rule.

In 2003, OMB issued Circular A-4 to provide guidance to federal agencies on the development of regulatory analysis as directed by Executive Order 12866.⁷ Circular A-4 states that it is designed to assist agencies by defining good regulatory analysis and standardizing the way benefits and costs of federal regulatory actions are measured and reported. In particular, the guidance provides for systematic evaluation of qualitative and quantitative benefits and costs, including their monetization. Circular A-4 also provides guidance on the selection of discount rates to adjust the estimated benefits and costs for differences in timing.⁸ According to Circular A-4, a regulatory impact analysis should include an evaluation of the benefits and costs of the proposed action and any reasonable alternatives, as well as a description of assumptions and uncertainty.⁹ It acknowledges that agencies cannot analyze all regulations according to a

⁷OMB, Circular A-4: Regulatory Analysis (Sept. 17, 2003).

⁸When the benefits and costs of a regulatory action will occur in the future, agencies must determine the present value of future benefits and costs by applying an appropriate discount rate—the interest rate used to convert benefits and costs occurring in different time periods to a common present value.

⁹Circular A-4 states that agencies should discount future benefits and costs using rates of 3 and 7 percent but notes that agencies may, in addition, consider a lower discount rate if a rule will have important intergenerational benefits or costs. In July 2014, we reported on the application of the guidance in Circular A-4 and the Technical Support Document and made recommendations to OMB to help clarify the relationship between those two documents. See GAO, *Environmental Regulation: EPA Should Improve Adherence to Guidance for Selected Elements of Regulatory Impact Analyses*, [GAO-14-519](#) (Washington, D.C.: July 18, 2014).

formula, and that different regulations may call for different emphases in the analysis. Executive Order 13563, which reaffirmed and supplemented Executive Order 12866 in 2011, generally directs federal agencies to conduct regulatory actions based on the best available science.¹⁰ It also directs agencies to use the best available techniques to quantify benefits and costs accurately.

Federal agencies began including estimates of the social cost of carbon in regulatory impact analyses following a decision by the U.S. Court of Appeals for the Ninth Circuit. Specifically, in 2006, the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) issued a final rule on fuel economy standards for certain vehicles which, like other regulations at the time, did not include estimates of the social cost of carbon.¹¹ The final rule stated that the agency had identified a benefit from a significant reduction in carbon dioxide emissions but stated that the dollar value of the benefit could not be determined because of the wide variation in published estimates of the social cost of carbon. In 2008, in response to a challenge from 11 states and several other organizations, the Ninth Circuit held that NHTSA had acted arbitrarily and capriciously by failing to monetize the value of carbon emissions reduction and directed NHTSA to include such a monetized value in an updated regulatory impact analysis for the regulation.¹² The court stated that, "[w]hile the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero."¹³ Following the court's decision, the Department of Energy, the Department of Transportation, and EPA incorporated a variety of individually developed estimates of the social cost of carbon into their regulatory analyses. These estimates were derived from academic literature and ranged, in general, from \$0 to \$159 (in 2006, 2007, or 2008 dollars) per metric ton of carbon dioxide emitted

¹⁰Exec. Order No. 13563, 76 Fed. Reg. 3821 (Jan. 18, 2011).

¹¹Average Fuel Economy Standards for Light Trucks Model Years 2008-2011, 71 Fed. Reg. 17,566 (Apr. 6, 2006). According to EPA officials, other regulations at the time did not typically quantify changes in carbon emissions.

¹²*Ctr. For Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1172, 1203 (9th Cir. 2008). The Ninth Circuit issued the 2008 opinion after vacating and withdrawing its prior opinion, 508 F.3d 508, issued on Nov. 15, 2007.

¹³*Id.* at 1200.

in 2007. They also varied in whether they reflected domestic or global measures of the social cost of carbon.¹⁴

In early 2009, in part to improve consistency in agencies' use of social cost of carbon estimates for regulatory impact analysis, OMB's Office of Information and Regulatory Affairs and the Council of Economic Advisers convened the Interagency Working Group on Social Cost of Carbon. The working group developed interim governmentwide social cost of carbon estimates based on an average of selected estimates published in academic literature. The interim estimates first appeared—and, thus, were first available for public review—in August 2009 in the Department of Energy's final rule on energy standards for vending machines.¹⁵ Agencies subsequently incorporated the interim estimates into several published regulatory actions that sought public comments to inform the development of final estimates for future use. The middle or "central" value for the range of interim estimates was \$19 (in 2006 dollars) per metric ton of carbon dioxide emitted in 2007.¹⁶

In October 2009, after developing the interim estimates, the working group reassembled to begin developing the final social cost of carbon estimates issued in the Technical Support Document. While the Technical Support Document is dated February 2010, it was first released publicly in March 2010 as an appendix to the Department of Energy's final rule on energy standards for small electric motors.¹⁷ Subsequently, dozens of published regulatory actions incorporated the estimates. The Technical

¹⁴The benefits and costs of reducing most greenhouse gas emissions, including carbon dioxide, differ from most other benefits and costs in at least two respects: (1) greenhouse gas emissions can contribute to global damages even when emitted in the United States because these emissions can disperse widely throughout the atmosphere, and (2) these emissions generally remain in the atmosphere for years, causing subsequent long-term damages. While Circular A-4 states that agencies should generally estimate domestic benefits and costs of regulations, it also provides latitude to include global economic effects resulting from regulations when relevant and states that such effects should be reported separately and in addition to domestic effects.

¹⁵Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines, 74 Fed. Reg. 44,914 (Aug. 31, 2009).

¹⁶The working group calculated five interim estimates of the social cost of carbon using different discount rate scenarios and referred to \$19—the middle of the five estimates—as the "central value."

¹⁷Energy Conservation Program: Energy Conservation Standards for Small Electric Motors, 75 Fed. Reg. 10,874 (Mar. 9, 2010).

Support Document states that the working group agreed to regularly update the social cost of carbon estimates as the research underlying the estimates evolves. In June 2013, after using the 2010 estimates in an earlier proposal of the rule, the Department of Energy’s final rule on energy standards for microwaves was the first regulatory action to incorporate the revised estimates developed by the working group in the 2013 update to the Technical Support Document.¹⁸ Table 1 shows the central values for the range of 2010 and 2013 social cost of carbon estimates for carbon emissions occurring in selected years.

Table 1: Central Values for the Social Cost of Carbon Estimates Issued by the Interagency Working Group on Social Cost of Carbon in 2010 and 2013

Dollars are 2007 dollars per metric ton of carbon dioxide

Year	2010 central values	2013 central values
2010	\$21	\$32
2020	26	43
2030	33	52
2040	39	61
2050	\$45	\$71

Source: Interagency Working Group on Social Cost of Carbon’s Technical Support Document and 2013 update. | GAO-14-663

Note: The Technical Support Document states that the working group calculated the social cost of carbon for emissions occurring in multiple future years to cover the time horizons anticipated for upcoming regulatory analysis. When the benefits and costs of a regulatory action will occur in the future, agencies must determine the present value of future benefits and costs by applying an appropriate discount rate—the interest rate used to convert benefits and costs occurring in different periods to a common present value. According to the Technical Support Document, the social cost of carbon estimates increase over time because future emissions are expected to produce larger incremental damages as the environment and the economy become more stressed in response to greater climate change. The working group selected four values of the social cost of carbon for regulatory analysis. The first three values are based on the average of estimates calculated at discount rates of 2.5 percent, 3 percent, and 5 percent, and the fourth value was included to represent higher-than-expected economic impacts at the 3 percent discount rate. The Technical Support Document refers to the average of estimates calculated at the 3 percent discount rate as the “central value” of the social cost of carbon and states that agencies should consider all four values when conducting regulatory analyses.

Appendix I lists regulatory actions from 2008 to 2014 and the type of social cost of carbon estimates (i.e., individually developed, interim, 2010, or 2013) incorporated in the actions’ regulatory analyses.

¹⁸Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens, 78 Fed. Reg. 36,316 (June 17, 2013).

Approach Used to Develop Estimates of the Social Cost of Carbon

According to the Technical Support Document and participants we interviewed, the working group consisted of participants representing six EOP offices and six federal agencies and was convened under Executive Order 12866. The working group's processes and methods for developing the estimates reflected three key principles. Specifically, according to participants, the working group (1) used consensus-based decision making; (2) relied largely on existing academic literature and models, including technical assistance from outside resources; and (3) took steps to disclose limitations and incorporate new information by considering public comments and revising the estimates as updated research became available.

Participating Entities

According to the Technical Support Document and participants we spoke with, OMB and the Council of Economic Advisers convened and led the working group, and four other EOP offices and six federal agencies actively participated in the group. According to several participants, the participating EOP offices included the relevant subject-matter experts to best contribute on behalf of the EOP,¹⁹ and the other participating agencies were those likely to conduct rulemakings affecting carbon emissions and, therefore, use the social cost of carbon estimates in the future. For example, EPA and the Department of Energy have issued numerous rules using the social cost of carbon estimates (see app. I).

OMB staff and EPA officials told us that OMB and the Council of Economic Advisers decided which EOP offices and federal agencies to invite to participate in the working group and, according to participants we interviewed from several agencies, each agency that chose to participate decided which of its internal offices would send representatives. OMB staff stated that any federal agency was welcome to participate in the working group, and EPA officials told us that at least two invited agencies declined to participate. OMB staff recalled that the working group generally included up to several participants from each participating office and agency and numbered approximately two dozen participants in total.

¹⁹We previously reported that four of these EOP offices—the Council on Environmental Quality, Office of Energy and Climate Change, OMB, and Office of Science and Technology Policy—provide high-level policy direction for federal climate change programs and activities and commonly lead formal and informal interagency initiatives on related issues. See GAO, *Climate Change: Improvements Needed to Clarify National Priorities and Better Align Them with Federal Funding Decisions*, [GAO-11-317](#) (Washington, D.C.: May 20, 2011).

Table 2 lists the 12 participating offices and agencies, along with the internal offices they sent to represent them on the working group.

Table 2: Offices and Agencies Participating in the Interagency Working Group on Social Cost of Carbon to Develop the 2010 and 2013 Social Cost of Carbon Estimates

Participating office or agency	2010 estimates	2013 estimates
Executive Office of the President		
Council of Economic Advisers ^a	X	X
Council on Environmental Quality	X	X
National Economic Council	X	X
Office of Energy and Climate Change ^b	X	X
Office of Management and Budget ^a	X	X
Office of Information and Regulatory Affairs		
Office of Science and Technology Policy	X	X
Federal agencies		
Department of Agriculture		
• Office of the Chief Economist	X	X
Department of Commerce ^c		
• International Trade Administration, Office of Competition and Economic Analysis ^d	X	
• National Oceanic and Atmospheric Administration, National Marine Fisheries Service ^e		X
Department of Energy ^f		
• Office of Climate Change Policy and Technology ^g	X	X
Department of Transportation		
• Office of the Secretary	X	X
• Volpe, The National Transportation Systems Center	X	
Department of the Treasury		
• Office of Economic Policy	X	
• Office of International Affairs, Office of Environment and Energy	X	X
Environmental Protection Agency		
• Office of Air and Radiation, Office of Atmospheric Programs	X	X
• Office of Policy, National Center for Environmental Economics	X	X

Source: GAO analysis of information provided by the Office of Management and Budget, Environmental Protection Agency, and Departments of Agriculture, Commerce, Energy, Transportation, and the Treasury. | GAO-14-663

^aThe Council of Economic Advisers and the Office of Management and Budget convened and led the working group to develop the 2010 and 2013 estimates.

^bIn March 2011, the Office of Energy and Climate Change joined the Domestic Policy Council.

^cAn official from the Department of Commerce's Economics and Statistics Administration told us that he attended two working group meetings as an observer during the development of the 2013 estimates, but that he did not review any materials produced by the group or otherwise contribute to the development of the estimates.

^dThe International Trade Administration's Office of Competition and Economic Analysis is now known as the Office of Trade and Economic Analysis.

^eAn official from the Department of Commerce's National Oceanic and Atmospheric Administration told us that she participated in the working group to develop the 2010 estimates while serving on detail to the Office of Science and Technology Policy.

^fA former Administrator of the Energy Information Administration told us that he participated as a technical advisor to the working group to develop the 2010 estimates and not as a representative of the Department of Energy. Participants told us that the Energy Information Administration also sent a representative to some working group meetings as an observer during the development of the 2013 estimates.

^gThe Office of Climate Change Policy and Technology is now known as the Office of Climate, Environment, and Efficiency.

In establishing the working group, several participants told us that OMB and the Council of Economic Advisers made efforts to ensure that the group's members, collectively, brought the necessary technical expertise for developing social cost of carbon estimates. For example, according to these participants and EPA documentation, participants from the EOP offices included individuals with expertise in pertinent topics, such as economics and climate science. The former Deputy Assistant Secretary for Environment and Energy at the Department of the Treasury stated that he was invited to participate in the working group because of his prior experience researching ways to discount costs and benefits across generations. In addition, the former Administrator of the Energy Information Administration told us that he was asked to participate, in part, based on his previous experience evaluating climate models while conducting research with the National Academy of Sciences. According to an OMB staff member, the six participating federal agencies were also responsible for ensuring that they provided adequate technical expertise to the working group. Agency representatives included environmental economists and climate scientists, among other key professionals. According to EPA documentation, participants from EPA also provided technical expertise in climate science, economics, and academic modeling to the broader group, as needed.

When the working group reconvened in 2013 to update the estimates, the same EOP offices and agencies generally participated, although some of the individuals participating on behalf of offices or agencies changed, in part due to individuals changing positions or leaving the government altogether. Also, some participants who previously had been serving details at other participating agencies had returned to their home agencies. For example, certain participants who were on detail to the

Council of Economic Advisers during the development of the 2010 Technical Support Document instead represented EPA on the working group during the development of the 2013 update.

According to the Technical Support Document, the working group was convened under the broad direction of Executive Order 12866 for agencies to assess the costs and benefits of intended regulations.²⁰ In addition, participants from several agencies told us that the executive order was the key requirement driving the working group's effort to develop social cost of carbon estimates. OMB staff stated that, while there is no single requirement or other approach for convening interagency working groups, it is appropriate for OMB to form interagency working groups to collaborate on policy or analytic needs identified under Executive Order 12866. These OMB staff members said that, instead of being organized under a written agreement or other requirements, the working group was an informal interagency working group with no charter or other convening document. According to OMB staff, there was no requirement that the informal working group should document its activities or proceedings, including the meetings held or specific discussions that occurred at each. However, OMB staff and EPA officials stated that all major issues discussed during working group meetings are documented in the Technical Support Document and its 2013 update, which is consistent with the control activities standard in the federal standards for internal control.²¹ We have also reported that interagency working groups use a variety of mechanisms to implement interagency collaborative efforts, including temporary working groups,²² and that not all collaborative arrangements, particularly those that are informal, need to be documented through written guidance and agreements.²³

²⁰The 2013 update to the Technical Support Document adds that Executive Order 13563, issued after the working group developed the 2010 social cost of carbon estimates, commits the administration to regulatory decision making based on the best available science.

²¹GAO, *Standards for Internal Control in the Federal Government*, [GAO/AIMD-00-21.3.1](#) (Washington, D.C.: November 1999).

²²GAO, [GAO-11-317](#); *Managing for Results: Key Considerations for Implementing Interagency Collaborative Mechanisms*, [GAO-12-1022](#) (Washington, D.C.: Sept. 27, 2012); and *Managing for Results: Implementation Approaches Used to Enhance Collaboration in Interagency Groups*, [GAO-14-220](#) (Washington, D.C.: Feb. 14, 2014).

²³[GAO-12-1022](#).

Processes and Methods

Participants told us that the working group's processes and methods reflected three key principles. First, the group used consensus-based decision making. Second, the group relied largely on existing academic literature and models, including technical assistance from outside resources. Third, the group took steps to disclose limitations and incorporate new information by considering public comments and revising the estimates as updated research became available.

Used Consensus-Based Decision Making

All of the participants we spoke with said that the working group used a consensus-based approach for making key decisions on developing the social cost of carbon estimates. Most participants said that the working group's overall approach was open and collegial, and that participants had many opportunities to make contributions and raise issues for discussion that were important to them.

OMB staff stated that the working group did not assign roles or responsibilities, and many participants told us that different working group participants and agencies volunteered to take responsibility for various aspects of the development of the estimates that fell within their particular areas of expertise. For example, OMB staff stated that, while OMB and the Council of Economic Advisers were the official leaders of the working group meetings, all EOP offices that participated played a large role during the meetings, and discussions were informal. According to these staff and other officials we spoke with, participants could generally choose the extent of their involvement, and all participants' contributions were considered equally.

According to many participants, the Council of Economic Advisers coordinated drafting the Technical Support Document, including gathering feedback from working group members. Specifically, they told us that, following the meetings, officials from the Council of Economic Advisers summarized the group discussions to include in the latest draft of the Technical Support Document and circulated draft sections of the Technical Support Document for the working group to review. For example, a participant told us that he raised concerns about whether the Technical Support Document provided adequate information on domestic measures of the social cost of carbon. The participant said that, in response to this feedback, the working group decided to include a separate discussion in the Technical Support Document on estimating domestic benefits and costs. The Technical Support Document states that reported domestic effects should be calculated using a range of values from 7 to 23 percent of the global measure of the social cost of carbon, although it cautions that these values are approximate, provisional, and

Relied on Existing Academic Literature and Models

highly speculative due to limited evidence. None of the participants we spoke with expressed concerns about how their contributions were incorporated into the final Technical Support Document. The participants generally stated that they were satisfied that the final Technical Support Document successfully addressed individual comments on the draft version and the overall consensus of the working group and its participating offices and agencies.

The Technical Support Document states that the main objective of the working group was to develop a range of estimates of the social cost of carbon using a defensible set of modeling inputs based on existing academic literature. Many participants confirmed that the working group relied largely on existing academic literature and models to develop its estimates. According to the Technical Support Document and many participants we spoke with, the working group calculated its estimates using three models that integrate climate and economic data into a single modeling framework for estimating future economic effects resulting from climate change.²⁴ In general, each model translates carbon dioxide emissions scenarios into changes in greenhouse gas concentrations in the atmosphere, greenhouse gas concentrations in the atmosphere into temperature changes, and temperature changes into net economic effects (i.e., damages and benefits). However, each model uses its own methods to estimate these effects. The Technical Support Document states that the three models are frequently cited in peer-reviewed literature. They have also been used in climate assessments by the Intergovernmental Panel on Climate Change—an organization within the United Nations that assesses scientific, technical, and economic information on the effects of climate change. In addition, the National Research Council of the National Academies recognized these three models as three of the most widely used models of their kind.²⁵

Many participants told us that the working group spent most of its meeting time reviewing and discussing academic literature to help decide on

²⁴The three models are Dynamic Integrated Climate and Economy (DICE), Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), and Policy Analysis of the Greenhouse Effect (PAGE). They were first developed in the early 1990s by researchers acknowledged as leaders in their field and are updated regularly based on new developments in climate and economic research.

²⁵National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington, D.C.: National Academies Press, 2010).

values for three key modeling inputs to run in each model. The key modeling inputs the working group selected were based on data from prevalent research organizations, such as the Stanford Energy Modeling Forum, and reflected the wide uncertainty in the academic literature, according to the Technical Support Document.²⁶ These inputs were as follows:

- scenarios for future population and economic growth (i.e., gross domestic product) and carbon dioxide emissions,
- a measure of the climate's responsiveness to increased concentrations of greenhouse gases in the atmosphere—known as equilibrium climate sensitivity,²⁷ and
- discount rates.

Several participants told us that different meetings focused on different modeling inputs and included technical presentations by participants with expertise in each technical area. For example, due to their previous experience working with the models, EPA officials made presentations on how each model works. OMB staff stated that the technical presentations focused on the academic materials cited in the Technical Support Document, including dozens of peer-reviewed journal articles. They also said that all technical decisions discussed in the Technical Support Document were arrived at by consensus through this process. Several participants said that a significant amount of the group's discussions focused on selecting discount rates that best reflect the most current academic literature, while also comports with OMB's guidance in Circular A-4. The Technical Support Document cites guidance from Circular A-4 in its discussion of many technical topics, including its selection of discount rates. It states that the discount rate (i.e., 3 percent) used to calculate the central value of the social cost of carbon estimates is consistent with Circular A-4 guidance. Some working group participants told us that they recognized the importance of using OMB guidance, including Circular A-4, in developing the Technical Support Document. The Technical Support Document states that the working group decided

²⁶The Stanford Energy Modeling Forum is an international forum for sharing and facilitating discussions on energy policy and global climate issues among researchers.

²⁷Equilibrium climate sensitivity is the long-term increase in the annual global-average surface temperature from a sustained doubling of the concentration of carbon dioxide in the atmosphere relative to preindustrial levels of the concentration of carbon dioxide in the atmosphere.

to calculate estimates for several discount rates (2.5, 3, and 5 percent) because the academic literature shows that the social cost of carbon is highly sensitive to the discount rate chosen, and because no consensus exists on the appropriate rate. It further states that, in light of such uncertainties, the working group determined that these three discount rates reflect reasonable judgments about the appropriate rate to use. Several participants stated that the working group chose this approach to capture varied concerns and interests, including participants' respective knowledge of the academic literature, on selecting the discount rate.

Once the working group agreed on these modeling inputs, EPA officials supervised their use in running the models to calculate the social cost of carbon estimates. All other model assumptions and features were unchanged by the working group, which weighted each model equally to calculate the final estimates. Several participants stated that an important principle for the leaders of the working group was that the working group reach consensus on the modeling inputs before running the models and agree, in advance, to accept the results based on the inputs selected, whatever the outcome. Through this approach, the working group developed a set of four social cost of carbon estimates for use in regulatory impact analyses. The first three values are based on the average of the estimates produced by all three models and selected modeling inputs at the three discount rates chosen. The fourth value was included to represent higher-than-expected economic impacts from climate change, and it is based on an average of certain values produced by each model at a 3 percent discount rate.²⁸ To capture uncertainties involved in regulatory impact analysis, the Technical Support Document emphasizes the importance of agencies considering all four estimates when conducting analyses.

According to EPA documentation and several participants, groups from outside the federal government did not participate in the working group, but the working group used some outside resources, specifically technical assistance. As noted in the Technical Support Document, the working group explored technical literature in relevant fields for developing the social cost of carbon estimates. Members of the working group

²⁸According to the Technical Support Document, the working group determined the fourth value by combining the values appearing at the furthest reaches of the distributions produced by each model. For this purpose, the working group used values produced from all three models for the 95th percentile at a 3 percent discount rate.

sometimes contacted researchers or developers of key data in an effort to ensure that the working group had a clear understanding of the information and how to use it. For example, according to several participants, members of the working group consulted with lead authors of a chapter on climate sensitivity that appears in the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.²⁹ According to the Technical Support Document, after consulting with the chapter authors, the working group was able to make some decisions to assist with statistical analyses needed to develop the social cost of carbon estimates. Many participants stated that the working group also consulted with the developers of the models used by the group to develop the estimates. For example, EPA officials told us that, while they conducted runs for one model that was readily available to the public, they spent a few days training with the developer of a second model before using it to conduct runs. They also contracted with the developer of a third model to run the model according to the decisions reached by the working group. They stated that they ran all of the 2013 estimates themselves, but that they continued to consult with the model developers to do so.

According to many participants and the 2013 update to the Technical Support Document, the only changes made to the models used for the 2013 revisions were those that the model developers incorporated into the latest versions of the models and that were subsequently used in peer-reviewed academic literature. Specifically, the developers updated the academic models to reflect new scientific information, such as in sea level rise and associated damages, resulting in higher estimates.³⁰ The working group did not make changes in the modeling inputs that it used

²⁹Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, et al. [eds.]) (Cambridge, UK: Cambridge University Press, 2007).

³⁰This new scientific information included an explicit representation of sea level rise and associated damages, updated climate change adaptation assumptions, and updated damage functions for agricultural impacts.

Took Steps to Disclose
Limitations and Incorporate
New Information

for the 2010 estimates.³¹ Several participants said that, while the original working group included frequent, hours-long meetings over several months, the working group assembled to discuss the 2013 revisions only met a few times. According to the 2010 Technical Support Document, the working group is committed to updating its estimates as the science and economic understanding of climate change and its impacts on society improve over time.

According to several participants and the Technical Support Document, the working group's processes and methods took steps to disclose limitations and incorporate new information by considering public comments and revising the estimates as updated economic and scientific research became available. The Technical Support Document discusses several limitations of its estimates and areas that the working group identified as being in particular need of additional exploration and research. For example, it points out that none of the three models accounts for damages from wildlife loss or ocean acidification caused by carbon dioxide emissions. Also, the models cannot completely predict how technology may adapt to warmer temperatures. In addition, according to the Technical Support Document, the models may not fully consider the effects of damages due to potential catastrophic events, such as the melting of Antarctic ice sheets. As a result of such limitations, the models may underestimate damages from increased carbon emissions, according to the Technical Support Document. The Technical Support Document states that, as a result of these limitations, the social cost of carbon estimates should continue to evolve as knowledge is gained, and available models improve. Some of the participating agencies have incorporated discussions of these limitations into regulatory impact analyses using social cost of carbon estimates. For example, in a 2012 rule setting pollution standards for certain power plants, EPA noted that

³¹In January 2014, a former coleader of the working group discussed some of the reasons behind this approach in a presentation before the annual meeting of the American Economic Association, a leading economic interest group. See Cass Sunstein, "On Not Revisiting Official Discount Rates: Institutional Inertia and the Social Cost of Carbon" (paper presented at the annual meeting of the American Economic Association, Philadelphia, PA, Jan. 3, 2014). In 2013, another former coleader of the working group published a paper detailing the working group's methodology. See Greenstone, Michael et al., "Developing a Social Cost of Carbon for U.S. Regulatory Analysis: A Methodology and Interpretation," *Review of Environmental Economics and Policy* 7, no. 1: 23-46 (2013).

the social cost of carbon estimates are subject to limitations and uncertainties.³²

Over the years, there have been opportunities for public comment on the various individually developed and working group estimates of the social cost of carbon for regulatory impact analysis, and several participants stated that these estimates were developed with input from the public. Since 2008, agencies have published over three dozen regulatory actions for public comment in the *Federal Register* that use various social cost of carbon estimates in regulatory impact analyses. While some of them specifically sought comments on the development of the social cost of carbon estimates used, and others did not, these regulatory actions were open to public comment, in general, for approximately 60 days and, according to OMB staff and other participants, agencies received many comments on the estimates through this process. Several participants stated that, while they discussed such public comments during working group meetings, individual agencies typically do not coordinate formally with other agencies on their reviews of comments received. According to the Technical Support Document, the working group convened, in part, to consider public comments on issues related to the social cost of carbon. After considering public comments on the interim values that agencies used in several rules, the working group developed the Technical Support Document, according to these participants and to the Technical Support Document. Several participants told us that the working group decided to revise the estimates for the first time in 2013 after agencies received a number of public comments encouraging revisions because the models used to develop the 2010 estimates had been subsequently updated and used in peer-reviewed academic literature. OMB staff stated that this theme was reflected in several public comments on regulations using the 2010 estimates.

In November 2013, OMB published a request in the *Federal Register* for public comments on all aspects of the Technical Support Document and

³²National Emission Standards for Hazardous Air Pollutants From Coal- and Oil-Fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units, 77 Fed. Reg. 9304 (Feb. 16, 2012).

its use of the models to develop estimates of the social cost of carbon.³³ The notice stated that OMB is particularly interested in comments on the selection of the models for use in developing the estimates, how the distribution of estimates should be represented in regulatory impact analyses, and the strengths and limitations of the overall approach. OMB staff told us that they decided to issue the request in response to calls for additional transparency, and that they received over 100 unique comments and thousands of identical form-letter comments in response to the request. They said that, since they were still reviewing the comments received, they had not yet decided on steps for responding to them, but that they expect to review them with the working group to determine whether they could inform future updates to the Technical Support Document. OMB staff stated that they have already made most of the comments publicly available online at <http://www.regulations.gov/> and that all of the comments would be made available soon.

The Technical Support Document states that the working group would regularly revisit the social cost of carbon estimates as new information becomes available due to improved scientific and economic research. The Technical Support Document set a goal of revisiting the estimates within 2 years, or when substantially updated models become available. Many participants told us that, to revise the estimates in 2013, the working group met only a few times and mostly for participants from EPA to present information about updates made to the models since the group last met in 2010. The updates touched on a variety of issues, including how some models represent damages from sea level rise. The 2013 update to the Technical Support Document states that it acknowledges the continued limitations described in the original Technical Support Document, and that it updates the estimates based on new versions of the underlying models without revisiting the working group's decisions on modeling inputs. Several participants stated that they reviewed drafts of the 2013 update to the Technical Support Document, but that there was little new information to review because only the models had been updated. In addition to stating that the working group would regularly

³³Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order No. 12866, 78 Fed. Reg. 70,586 (Nov. 26, 2013). In January 2014, OMB extended the public comment period through February 26, 2014. See Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order No. 12866, 79 Fed. Reg. 4359 (Jan. 27, 2014).

revisit its estimates, the Technical Support Document states that the working group will continue to support research to improve the estimates and hopes to develop methods to value other greenhouse gases as part of its ongoing work.³⁴

Agency Comments

We provided a draft of this report for review and comment to the Departments of Agriculture, Commerce, Energy, Transportation, and the Treasury; EPA; and OMB. Only the Department of the Treasury provided written comments, which we received on July 14, 2014, and are reproduced in appendix II; in its written comments, the Department of the Treasury stated that the draft report does a good job of capturing the interagency process through which the estimates of the social cost of carbon were developed. In oral comments provided on July 15, 2014, OMB staff confirmed that OMB generally agreed with the report findings. OMB staff also provided technical comments, which we incorporated into the report, as appropriate. The Department of Energy and EPA provided technical comments only, which we incorporated into the report, as appropriate. In e-mails received on July 1, July 9, and July 14, 2014, respectively, the liaisons from the Departments of Agriculture, Commerce, and Transportation stated that the departments did not have any comments on the draft report.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies to the appropriate congressional committees; the Secretaries of Agriculture, Commerce, Energy, Transportation, and the Treasury; the Administrator of EPA; the

³⁴In late 2010 and early 2011, EPA and the Department of Energy sponsored two workshops on valuing climate change damages for regulatory analysis. The agencies reported that they sponsored the workshops to prepare for and inform future working group activities. See ICF International, *Workshop Report: Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis – Part 1* (January 2011); summary of workshop sponsored by EPA and the Department of Energy and titled “Modeling Climate Change Impacts and Associated Economic Damages” (Washington, D.C.: Nov. 18-19, 2010) and *Workshop Report: Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis – Part 2* (March 2011); summary of workshop sponsored by EPA and the Department of Energy and titled “Research on Climate Change Impacts and Associated Economic Damages” (Washington, D.C., Jan. 27-28, 2011).

Director of OMB; and other interested parties. In addition, the report will be available at no charge on the GAO website at <http://www.gao.gov>.

If you or your staff members have any questions about this report, please contact me at (202) 512-3841 or gomezj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. Key contributors to this report are listed in appendix III.

A handwritten signature in black ink, reading "Alfredo Gómez". The signature is written in a cursive style with a large, stylized "A" and "G".

J. Alfredo Gómez
Director, Natural Resources and Environment

Appendix I: Regulatory Actions, by Agency and Type of Social Cost of Carbon Estimates Used, 2008-2014

This appendix lists regulatory actions from 2008 to 2014 and the type of social cost of carbon estimates used (i.e., individually developed, interim, 2010, or 2013) in the actions' regulatory impact analyses. For each regulatory action, table 3 lists the date published in the *Federal Register*, the agency conducting the action, the name and status of the rule associated with the action, and the action's citation in the *Federal Register*.

Table 3: Regulatory Actions, by Agency and Type of Social Cost of Carbon Estimates Used in the Regulatory Impact Analysis, 2008-2014

Date published in the <i>Federal Register</i>	Agency	Rule	Status of rule	<i>Federal Register</i> citation
Individually developed agency estimates				
May 2, 2008	Department of Transportation (Transportation), National Highway Traffic Safety Administration (NHTSA)	Average Fuel Economy Standards, Passenger Cars and Light Trucks; Model Years 2011-2015	Proposed	73 Fed. Reg. 24,352
July 30, 2008	Environmental Protection Agency (EPA)	Regulating Greenhouse Gas Emissions Under the Clean Air Act	Advanced Notice of Proposed Rulemaking	73 Fed. Reg. 44,354
Aug. 25, 2008	Department of Energy (Energy)	Energy Conservation Program for Commercial and Industrial Equipment: Energy Conservation Standards for Commercial Ice-Cream Freezers; Self-Contained Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers Without Doors; and Remote Condensing Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers	Proposed	73 Fed. Reg. 50,072
Oct. 7, 2008	Energy	Energy Conservation Program for Commercial and Industrial Equipment: Packaged Terminal Air Conditioner and Packaged Terminal Heat Pump Energy Conservation Standards	Final	73 Fed. Reg. 58,772

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and Type of Social Cost of Carbon Estimates
Used, 2008-2014**

Date published in the Federal Register	Agency	Rule	Status of rule	Federal Register citation
Oct. 17, 2008	Energy	Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Electric and Gas Kitchen Ranges and Ovens, and Microwave Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers)	Proposed	73 Fed. Reg. 62,034
Jan. 9, 2009	Energy	Energy Conservation Program for Commercial and Industrial Equipment: Energy Conservation Standards for Commercial Ice- Cream Freezers; Self-Contained Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers Without Doors; and Remote Condensing Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator- Freezers	Final	74 Fed. Reg. 1092
Mar. 30, 2009	Transportation, NHTSA	Average Fuel Economy Standards Passenger Cars and Light Trucks Model Year 2011	Final	74 Fed. Reg. 14,196
Apr. 8, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Microwave Ovens, and Electric and Gas Kitchen Ranges and Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers)	Final	74 Fed. Reg. 16,040
Apr. 13, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for General Service Fluorescent Lamps and Incandescent Reflector Lamps	Proposed	74 Fed. Reg. 16,920
May 26, 2009	EPA	Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program	Proposed	74 Fed. Reg. 24,904
May 29, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines	Proposed	74 Fed. Reg. 26,020

**Appendix I: Regulatory Actions, by Agency
and Type of Social Cost of Carbon Estimates
Used, 2008-2014**

Date published in the <i>Federal Register</i>	Agency	Rule	Status of rule	<i>Federal Register</i> citation
July 14, 2009	Energy	Energy Conservation Program: Energy Conservation Standards and Test Procedures for General Service Fluorescent Lamps and Incandescent Reflector Lamps	Final	74 Fed. Reg. 34,080
July 22, 2009	Energy	Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	Final	74 Fed. Reg. 36,312
Interim governmentwide estimates				
Aug. 31, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines	Final	74 Fed. Reg. 44,914
Sep. 28, 2009	EPA and Transportation, NHTSA	Proposed Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards	Proposed	74 Fed. Reg. 49,454
Nov. 9, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Microwave Ovens, and Electric and Gas Kitchen Ranges and Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers)	Supplemental Notice of Proposed Rulemaking	74 Fed. Reg. 57,738
Nov. 24, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for Small Electric Motors	Proposed	74 Fed. Reg. 61,410
Dec. 11, 2009	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters	Proposed	74 Fed. Reg. 65,852
Jan. 8, 2010	Energy	Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Microwave Ovens, and Electric and Gas Kitchen Ranges and Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers)	Final	75 Fed. Reg. 1122

**Appendix I: Regulatory Actions, by Agency
and Type of Social Cost of Carbon Estimates
Used, 2008-2014**

Date published in the Federal Register	Agency	Rule	Status of rule	Federal Register citation
Mar. 26, 2010	EPA	Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program	Final	75 Fed. Reg. 14,670
June 21, 2010	EPA	Hazardous and Solid Waste Management System; Identification and Listing of Special Wastes; Disposal of Coal Combustion Residuals From Electric Utilities	Proposed	75 Fed. Reg. 35,128
2010 governmentwide estimates				
Mar. 9, 2010	Energy	Energy Conservation Program: Energy Conservation Standards for Small Electric Motors	Final	75 Fed. Reg. 10,874
Apr. 16, 2010	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters	Final	75 Fed. Reg. 20,112
May 7, 2010	EPA and Transportation, NHTSA	Light Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards	Final	75 Fed. Reg. 25,324
May 28, 2010	Transportation, Federal Aviation Administration	Automatic Dependent Surveillance—Broadcast (ADS-B) Out Performance Requirements to Support Air Traffic Control (ATC) Service	Final	75 Fed. Reg. 30,160
Aug. 2, 2010	EPA	Federal Implementation Plans To Reduce Interstate Transport of Fine Particulate Matter and Ozone	Proposed	75 Fed. Reg. 45,210
Sep. 9, 2010	EPA	National Emission Standards for Hazardous Air Pollutants from the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants	Final	75 Fed. Reg. 54,970
Oct. 14, 2010	EPA	Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Sewage Sludge Incineration Units	Proposed	75 Fed. Reg. 63,260
Nov. 30, 2010	EPA and Transportation, NHTSA	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles	Proposed	75 Fed. Reg. 74,152

**Appendix I: Regulatory Actions, by Agency
and Type of Social Cost of Carbon Estimates
Used, 2008-2014**

Date published in the <i>Federal Register</i>	Agency	Rule	Status of rule	<i>Federal Register</i> citation
Mar. 14, 2011	EPA	National Emission Standards for Hazardous Air Pollutants: Mercury Emissions from Mercury Cell Chlor-Alkali Plants	Supplemental Proposed Rule	76 Fed. Reg. 13,852
Mar. 21, 2011	EPA	Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Sewage Sludge Incineration Units	Final	76 Fed. Reg. 15,372
Mar. 21, 2011	EPA	National Emission Standards for Hazardous Air Pollutants for Major Sources: Industrial, Commercial, and Institutional Boilers and Process Heaters	Final	76 Fed. Reg. 15,608
Apr. 11, 2011	Energy	Energy Conservation Program: Energy Conservation Standards for Fluorescent Lamp Ballasts	Proposed	76 Fed. Reg. 20,090
Apr. 21, 2011	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners	Direct Final	76 Fed. Reg. 22,454
June 27, 2011	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Furnaces and Residential Central Air Conditioners and Heat Pumps	Direct Final	76 Fed. Reg. 37,408
Aug. 8, 2011	EPA	Federal Implementation Plans: Interstate Transport of Fine Particulate Matter and Ozone and Correction of SIP Approvals ^a	Final	76 Fed. Reg. 48,208
Sep. 15, 2011	EPA and Transportation, NHTSA	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles	Final	76 Fed. Reg. 57,106
Sep. 15, 2011	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers	Final	76 Fed. Reg. 57,516
Nov. 14, 2011	Energy	Energy Conservation Program: Energy Conservation Standards for Fluorescent Lamp Ballasts	Final	76 Fed. Reg. 70,548
Dec. 1, 2011	EPA and Transportation, NHTSA	2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards	Proposed	76 Fed. Reg. 74,854

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Used, 2008-2014**

Date published in the Federal Register	Agency	Rule	Status of rule	Federal Register citation
Dec. 23, 2011	EPA	Commercial and Industrial Solid Waste Incineration Units: Reconsideration and Proposed Amendments; Non-Hazardous Secondary Materials That Are Solid Waste	Proposed	76 Fed. Reg. 80,452
Jan. 17, 2012	Energy	Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	Proposed	77 Fed. Reg. 2356
Feb. 10, 2012	Energy	Energy Conservation Program: Energy Conservation Standards for Distribution Transformers	Proposed	77 Fed. Reg. 7282
Feb. 14, 2012	Energy	Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwaves	Supplemental Notice of Proposed Rulemaking	77 Fed. Reg. 8526
Feb. 16, 2012	EPA	National Emission Standards for Hazardous Air Pollutants from Coal- and Oil-Fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units	Final	77 Fed. Reg. 9304
Mar. 27, 2012	Energy	Energy Conservation Program: Energy Conservation Standards for Battery Chargers and External Power Supplies	Proposed	77 Fed. Reg. 18,478
Apr. 13, 2012	EPA	Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units	Proposed	77 Fed. Reg. 22,392
May 30, 2012	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Dishwashers	Direct Final	77 Fed. Reg. 31,918
May 31, 2012	Energy	Energy Conservation Program: Energy Conservation Standards for Residential Clothes Washers	Direct Final	77 Fed. Reg. 32,308
Oct. 15, 2012	EPA and Transportation, NHTSA	2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards	Final	77 Fed. Reg. 62,624

**Appendix I: Regulatory Actions, by Agency
and Type of Social Cost of Carbon Estimates
Used, 2008-2014**

Date published in the <i>Federal Register</i>	Agency	Rule	Status of rule	<i>Federal Register</i> citation
Apr. 18, 2013	Energy	Energy Conservation Program: Energy Conservation Standards for Distribution Transformers	Final	78 Fed. Reg. 23,336
June 7, 2013	EPA	Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category	Proposed	78 Fed. Reg. 34,432
2013 revised governmentwide estimates				
June 17, 2013	Energy	Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens	Final	78 Fed. Reg. 36,316
Aug. 20, 2013	Energy	Energy Conservation Program: Energy Conservation Standards for Metal Halide Lamp Fixtures	Proposed	78 Fed. Reg. 51,464
Sep. 11, 2013	Energy	Energy Conservation Program: Energy Conservation Standards for Walk-In Coolers and Freezers	Proposed	78 Fed. Reg. 55,782
Sep. 11, 2013	Energy	Energy Conservation Program: Energy Conservation Standards for Commercial Refrigeration Equipment	Proposed	78 Fed. Reg. 55,890
Oct. 25, 2013	Energy	Energy Conservation Program for Consumer Products: Energy Conservation Standards for Residential Furnace Fans	Proposed	78 Fed. Reg. 64,068
Dec. 6, 2013	Energy	Energy Conservation Program: Energy Conservation Standards for Commercial and Industrial Electric Motors	Proposed	78 Fed. Reg. 73,590
Jan. 8, 2014	EPA	Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units	Proposed	79 Fed. Reg. 1430
Feb. 10, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for Metal Halide Lamp Fixtures	Final	79 Fed. Reg. 7746
Feb. 10, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for External Power Supplies	Final	79 Fed. Reg. 7846
Mar. 4, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for Commercial Clothes Washers	Proposed	79 Fed. Reg. 12,302

**Appendix I: Regulatory Actions, by Agency
and Type of Social Cost of Carbon Estimates
Used, 2008-2014**

Date published in the <i>Federal Register</i>	Agency	Rule	Status of rule	<i>Federal Register</i> citation
Mar. 17, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for Automatic Commercial Ice Makers	Proposed	79 Fed. Reg. 14,846
Mar. 28, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for Commercial Refrigeration Equipment	Final	79 Fed. Reg. 17,726
Apr. 29, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for General Service Fluorescent Lamps and Incandescent Reflector Lamps	Proposed	79 Fed. Reg. 24,068
May 29, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for Commercial and Industrial Electric Motors	Final	79 Fed. Reg. 30,934
June 3, 2014	Energy	Energy Conservation Program: Energy Conservation Standards for Walk-In Coolers and Freezers	Final	79 Fed. Reg. 32,050
June 18, 2014	EPA	Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units	Proposed	79 Fed. Reg. 34,830

Sources: Environmental Protection Agency and *Federal Register*. | GAO-14-663

Notes:

Regulatory actions in this table are as of June 18, 2014.

In 2008 and early 2009, individual estimates of the social cost of carbon were developed by each agency and typically based on estimates published in academic literature. The interim governmentwide estimates were developed in early 2009 by the Interagency Working Group on Social Cost of Carbon and derived from an average of selected estimates published in academic literature. The 2010 governmentwide estimates were developed by the Interagency Working Group on Social Cost of Carbon and issued in its February 2010 Technical Support Document. The 2013 revised governmentwide estimates were developed by the Interagency Working Group on Social Cost of Carbon and issued in a May 2013 update to the Technical Support Document, which was reissued with minor technical corrections in November 2013.

^aSIP refers to State Implementation Plan.

Appendix II: Comments from the Department of the Treasury



DEPARTMENT OF THE TREASURY
WASHINGTON, D.C.

JUL 14 2014

TO: Director J. Alfredo Gomez, Government Accountability Office

FROM: Leonardo Martinez-Diaz, Deputy Assistant Secretary for Energy and Environment

RE: Draft report on Development of Social Cost of Carbon Estimate (361544)

Dear Director Gomez,

Thank you for the opportunity to review the draft report on the Development of the Social Cost of Carbon Estimates (361544). The report does a good job of capturing the interagency process through which the estimates of the social cost of carbon were developed. We have no further comments on the draft.

Sincerely,

A handwritten signature in black ink, appearing to read "Leonardo Martinez-Diaz", written over a stylized graphic element that resembles a large, abstract letter 'L' or a signature flourish.

Leonardo Martinez-Diaz

Appendix III: GAO Contact and Staff Acknowledgments

GAO Contact

J. Alfredo Gómez, (202) 512-3841, or gomezj@gao.gov

Staff Acknowledgments

In addition to the individual named above, Janet Frisch (Assistant Director), Elizabeth Beardsley, Stephanie Gaines, Cindy Gilbert, Chad M. Gorman, Tim Guinane, Patricia Moye, Susan Offutt, Alison O'Neill, and Kiki Theodoropoulos made key contributions to this report.

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Chuck Young, Managing Director, youngc1@gao.gov, (202) 512-4800, U.S. Government Accountability Office, 441 G Street NW, Room 7149, Washington, DC 20548



Exhibit 13



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

JUN 06 2011

ASSISTANT ADMINISTRATOR
FOR ENFORCEMENT AND
COMPLIANCE ASSURANCE

Mr. Jose W. Fernandez
Assistant Secretary
Economic, Energy and Business Affairs
U.S. Department of State
Washington, DC 20520

Dr. Kerri-Ann Jones
Assistant Secretary
Oceans and International Environmental and Scientific Affairs
U.S. Department of State
Washington, DC 20520

Dear Mr. Fernandez and Dr. Jones:

In accordance with our authorities under the National Environmental Policy Act (NEPA), the Council on Environmental Quality (CEQ) NEPA regulations, and Section 309 of the Clean Air Act, EPA has reviewed the Supplemental Draft Environmental Impact Statement (SDEIS) for TransCanada's proposed Keystone XL Project ("Project").

EPA reviewed the Draft Environmental Impact Statement (DEIS) for this project and submitted comments in July of 2010. At that time EPA rated the DEIS as "Inadequate-3" because potentially significant impacts were not evaluated and additional information and analyses were necessary to ensure that the EIS fully informed decision makers and the public about potential consequences of the Keystone XL Project. Since that time, the State Department has worked diligently to develop additional information and analysis in response to EPA's comments and the large number of other comments received on the DEIS. The State Department also made a very constructive decision to seek further public review and comment through publication of the SDEIS, to help the public and decision makers carefully weigh the environmental costs and benefits of transporting oil sands crude from Canada to delivery points in Oklahoma and Texas. The consideration of the environmental impacts associated with constructing and operating this proposed pipeline is especially important given that current excess pipeline capacity for transporting oil sands crude to the United States will likely persist until after 2020, as noted in the SDEIS.

While the SDEIS has made progress in responding to EPA's comments on the DEIS and providing information necessary for making an informed decision, EPA believes additional analysis is necessary to fully respond to our earlier comments and to ensure a full evaluation of

the potential impacts of proposed Project, and to identify potential means to mitigate those impacts. As EPA and the State Department have discussed many times, EPA recommends that the State Department improve the analysis of oil spill risks and alternative pipeline routes, provide additional analysis of potential impacts to communities along the pipeline route and adjacent to refineries and the associated environmental justice concerns, together with ways to mitigate those impacts, improve the discussion of lifecycle greenhouse gas emissions (GHGs) associated with oil sands crude, and improve the analysis of potential impacts to wetlands and migratory bird populations. We are encouraged by the State Department's agreement to include some of these additional analyses in the Final Environmental Impact Statement (Final EIS). We have noted those agreements in this letter, and look forward to working with you to develop these analyses for the Final EIS.

Pipeline Safety/Oil Spill Risks

EPA is the lead federal response agency for responding to oil spills occurring in and around inland waters. As part of that responsibility, we have considerable experience working to prevent and respond to oil spills. Pipeline oil spills are a very real concern, as we saw during the two pipeline spills in Michigan and Illinois last summer. Just in the last month, the Keystone Pipeline experienced two leaks (in North Dakota and Kansas), one of which was brought to the company's attention by a local citizen. These leaks resulted in shut-downs and issuance of an order to TransCanada from the Pipeline and Hazardous Materials Safety Administration (PHMSA), requiring that corrective measures be taken prior to the subsequently approved restart of operations. PHMSA's Order of June 3, 2011 for the Keystone Pipeline – which also carries Canadian oil sands crude oil and is operated by the same company as the proposed Keystone XL Project – was based on the hazardous nature of the product that the pipeline transports and the potential that the conditions causing the failures that led to the recent spills were present elsewhere on the pipeline. These events, which occurred after EPA's comment letter on the DEIS, underscore the comments about the need to carefully consider both the route of the proposed Keystone XL Pipeline and appropriate measures to prevent and detect a spill.

We have several recommendations for additional analyses that relate to the potential for oil spills, as well as the potential impacts and implications for response activities in the event of a pipeline leak or rupture. We recommend and appreciate your agreement that the Final EIS use data from the National Response Center, which reports a more comprehensive set of historical spill events than the Pipeline and Hazardous Material Safety Administration's incident database, to assess the risk of a spill from the proposed pipeline. With respect to the spill detection systems proposed by the applicant, we remain concerned that relying solely on pressure drops and aerial surveys to detect leaks may result in smaller leaks going undetected for some time, resulting in potentially large spill volumes. In light of those concerns, we also appreciate your agreement that the Final EIS consider additional measures to reduce the risks of undetected leaks. For example, requiring ground-level inspections of valves and other parts of the system several times per year, in addition to aerial patrols, could improve the ability to detect leaks or spills and minimize any damage.

The SDEIS indicates that there may be a "minor" increase in the number of mainline valves installed to isolate pipeline segments and limit impacts of a spill, compared to what was

originally reported in the DEIS (SDEIS, pg. 2-4). However, no detailed information or decision criteria are provided with regard to the number of valves, or their location. In order to evaluate potential measures to mitigate accidental releases, we appreciate your agreement to provide additional information in the Final EIS on the number and location of the valves that will be installed and to evaluate the feasibility of increasing the number of valves in more vulnerable areas. For example, it may be appropriate to increase the number of valves where the water table is shallow, or where an aquifer is overlain by highly permeable soils, such as the Ogallala aquifer. We also recommend consideration of external pipe leak detection systems in these areas to improve the ability to detect pinhole (and greater) leaks that could be substantial, yet below the sensitivity of the currently proposed leak detection systems. In addition, while we understand that valves are not proposed to be located at water crossings that are less than 100 feet wide, we recommend that the Final EIS nevertheless consider the potential benefits of installing valves at water crossings less than 100 feet wide where there are sensitive aquatic resources.

Predicting the fate and transport of spilled oil is also important to establish potential impacts and develop response strategies. While the SDEIS provides additional information about the different classes of crude oils that may be transported, we recommend the Final EIS evaluate each class of crude that will be transported, how it will behave in the environment, and qualitatively discuss the potential issues associated with responding to a spill given different types of crude oils and diluents used.

With regard to the chemical nature of the diluents that are added to reduce the viscosity of bitumen, the SDEIS states "the exact composition may vary between shippers and is considered proprietary information" (SDEIS, pg. 3-104). We believe an analysis of potential diluents is important to establish the potential health and environmental impacts of any spilled oil, and responder/worker safety, and to develop response strategies. In the recent Enbridge oil spill in Michigan, for example, benzene was a component of the diluent used to reduce the viscosity of the oil sands crude so that it could be transported through a pipeline. Benzene is a volatile organic compound, and following the spill in Michigan, high benzene levels in the air prompted the issuance of voluntary evacuation notices to residents in the area by the local county health department. Similarly, although the SDEIS provides additional information on the potential impact of spills on groundwater, we recommend that the Final EIS improve the risk assessment by including specific information on the groundwater recharge areas along the pipeline route, recognizing that these areas are more susceptible to groundwater contamination from oil spills.

We appreciate that the SDEIS provides additional information about the feasibility of alternative pipeline routes that would reduce the risk of adverse impacts to the Ogallala aquifer, by re-routing the pipeline so it does not cross the aquifer. Many commenters, including EPA, expressed concerns over the potential impacts to this important resource during the review of the DEIS. If a spill did occur, the potential for oil to reach groundwater in these areas is relatively high given shallow water table depths and the high permeability of the soils overlying the aquifer. In addition, we are concerned that crude oil can remain in the subsurface for decades, despite efforts to remove the oil and natural microbial remediation.

However, the SDEIS concludes that the alternative routes that avoid the Ogallala aquifer are not reasonable, and consequently does not provide a detailed evaluation of the environmental impacts of routes other than the applicant's proposed route. The SDEIS indicates that no other alternatives are considered in detail because, in part, they do not offer an overall environmental advantage compared to other routes. In support of this conclusion the SDEIS presents a limited analysis of the potential environmental impacts of the alternative routes and offers qualitative judgments about the relative severity of impacts to different resources, e.g., considering potential impacts from spills to the Ogallala aquifer less important than impacts to surface waters from a spill associated with an additional crossing of the Missouri River. We think this limited analysis does not fully meet the objectives of NEPA and CEQ's NEPA regulations, which provide that agencies rigorously explore and objectively evaluate reasonable alternatives. CEQ guidance states that reasonable alternatives include those that are practical or feasible from the technical and economic standpoint and using common sense.¹ Recognizing the regional significance of these groundwater resources, we recommend that the State Department re-evaluate the feasibility of these alternative routes and more clearly outline the environmental, technical and economic reasons for not considering other alternative routes in more detail as part of the NEPA analysis.

Oil Spill Impacts on Affected Communities and Environmental Justice Concerns

The communities facing the greatest potential impact from spills are of course the communities along the pipeline route. We are concerned that the SDEIS does not adequately recognize that some of these communities may have limited emergency response capabilities and consequently may be more vulnerable to impacts from spills, accidents and other releases. This is particularly likely to be true of minority, low-income and Tribal communities or populations along the pipeline route. We appreciate your agreement to address this issue in the Final EIS by clarifying the emergency response capability of each county along the pipeline route using the plans produced by Local Emergency Planning Committees. We also appreciate your agreement to identify potential mitigation measures in the Final EIS based on this information. We look forward to working with your staff to identify data sources and approaches for addressing these issues.

As part of this analysis, we are concerned that the SDEIS may have underestimated the extent to which there are communities along the pipeline with less capacity to respond to spills and potentially associated health issues, particularly minority, low-income or Tribal communities. We appreciate your agreement to re-evaluate in the Final EIS which communities may have such capacity issues by adopting the more commonly-used threshold of 20% higher low-income, minority or Tribal population compared to the general population, instead of the 50% used in the SDEIS.

With respect to data on access to health care, we are encouraged that the SDEIS provided critically important information on medically underserved areas and on health professional shortage areas. We will provide recommendations on methods to present this data to make it

¹ 40 CFR 1502.14; "Forty Most Asked Questions Concerning CEQ's National Environmental Policy Act Regulations," 46 FR 18026 (1981) - Question 2a: Alternatives Outside the Capability of Applicant or Jurisdiction of Agency.

more meaningful to reviewers and will work with your staff as you move towards publishing a Final EIS.

The SDEIS does recognize that minority, low-income or Tribal populations may be more vulnerable to health impacts from an oil spill, and we appreciate the applicant's commitment to provide an alternative water supply "if an accidental release from the proposed Project that is attributable to Keystone's actions contaminates groundwater or surface water used as a source of potable water or for irrigation or industrial purposes..." (SDEIS, pg. 3-154). Further, the SDEIS states that impacts would be mitigated by the applicant's liability for costs associated with cleanup, restoration and compensation for any release that could affect surface water (SDEIS, pg. 3-154). We believe that this mitigation measure should also apply for releases that could affect groundwater. Finally, we recommend that the Final EIS evaluate additional mitigation measures that would avoid and minimize potential impacts through all media (i.e., surface and ground water, soil, and air) to minority, low-income and Tribal populations rather than rely solely on after-the-fact compensation measures. Some examples of additional mitigation include developing a contingency plan before operations commence for emergency response and remedial efforts to control the contamination. This would also include providing notification to individuals affected by soil or groundwater contamination, ensuring the public is knowledgeable and aware of emergency procedures and contingency plans (including posting procedures in high traffic visibility areas), and providing additional monitoring of air emissions and conducting medical monitoring and/or treatment responses where necessary.

Environmental and Health Impacts to Communities Adjacent to Refineries

We are also concerned with the conclusion that there are no expected disproportionate adverse impacts to minority or low-income populations located near refineries that are expected to receive the oil sands crude, particularly because many of these communities are already burdened with large numbers of high emitting sources of air pollutants. It is not self-evident that the addition of an 830,000 barrels per day capacity pipeline from Canada to refineries in the Gulf Coast will have no effect on emissions from refineries in that area. We recommend that the Final EIS re-examine the potential likelihood of increased refinery emissions, and provide a clearer analysis of potential environmental and health impacts to communities from refinery air emissions and other environmental stressors. As part of this re-evaluation, we encourage the State Department to provide more opportunities for people in these potentially affected communities to have meaningful engagement, including additional public meetings, particularly in Port Arthur, Texas, before publication of the Final EIS. Public meetings in these potentially affected communities provide an opportunity for citizens to present their concerns, and also for the State Department to clearly explain its analysis of potential impacts associated with the proposed project to the people potentially affected.

Lifecycle GHG Emissions

We appreciate the State Department's efforts to improve the characterization of lifecycle GHG emissions associated with Canadian oil sands crude. The SDEIS confirms, for example, that Canadian oil sands crude are GHG-intensive relative to other types of crude oil, due primarily to increased emissions associated with extraction and refining.

The SDEIS also includes an important discussion of lifecycle GHG emissions associated with oil sands crude and provides quantitative estimates of potential incremental impacts associated with the proposed Project. For example, the SDEIS (pg. 3-198) states that under at least one scenario, additional annual lifecycle GHG emissions associated with oil sands crude compared to Middle East Sour crude are 12 to 23 million metric tons of CO₂ equivalent (CO₂-e) at the proposed Project pipeline's full capacity (roughly the equivalent of annual emissions from 2 to 4 coal-fired power plants).² While we appreciate the inclusion of such estimates, EPA believes that the methodology used by the State Department and its contractors to calculate those estimates may underestimate the values at the high-end of the ranges cited in the lifecycle GHG emissions discussion by approximately 20 percent. We will continue to work with your staff to address this concern as you move towards publishing a Final EIS.

Further, in discussing these lifecycle GHG emissions, the SDEIS concludes "on a global scale, emissions are not likely to change" (SDEIS, pg. 3-197). We recommend against comparing GHG emissions associated with a single project to global GHG emission levels. As recognized in CEQ's draft guidance concerning the consideration of GHG emissions in NEPA analyses, "[T]he global climate change problem is much more the result of numerous and varied sources, each of which might seem to make a relatively small addition to global atmospheric GHG concentrations."³

Moreover, recognizing the proposed Project's lifetime is expected to be at least fifty years, we believe it is important to be clear that under at least one scenario, the extra GHG emissions associated with this proposed Project may range from 600 million to 1.15 billion tons CO₂-e, assuming the lifecycle analysis holds over time (and using the SDEIS' quantitative estimates as a basis). In addition, we recommend that the Final EIS explore other means to characterize the impact of the GHG emissions, including an estimate of the "social cost of carbon" associated with potential increases of GHG emissions.⁴ The social cost of carbon includes, but is not limited to, climate damages due to changes in net agricultural productivity, human health, property damages from flood risk, and ecosystem services due to climate change. Federal agencies use the social cost of carbon to incorporate the social benefits of reducing CO₂ emissions into analyses of regulatory actions that have a marginal impact on cumulative global emissions; the social cost of carbon is also used to calculate the negative impacts of regulatory actions that increase CO₂ emissions.

Finally, we continue to be concerned that the SDEIS does not discuss opportunities to mitigate the entire suite of GHG emissions associated with constructing the proposed Project. We appreciate your agreement to identify practicable mitigation measures in the Final EIS for

² <http://www.epa.gov/cleanenergy/energy-resources/calculator.html>

³ "Draft NEPA Guidance on Consideration of the Effects of Climate Change and Greenhouse Gas Emissions," (February 18, 2010)

⁴ "Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866;" Interagency Working Group on Social Cost of Carbon, United States Government, February 2010. Presents four estimates of estimated monetized damages associated with a ton of CO₂ released in 2010 (\$5, \$21, \$35, \$65) (\$2007); these estimates grow over time and are associated with different discount rates.

GHG emissions associated with operation of the pipeline in the United States. As part of that analysis, we recommend consideration of opportunities for energy efficiency and utilization of green power for pipeline operations. In addition, we recommend a discussion of mitigation approaches for GHG emissions from extraction activities that are either currently or could be employed to help lower lifecycle GHG emissions to levels closer to those of conventional crude oil supplies. We recommend that this discussion include a detailed description of efforts ongoing and under consideration by producers, as well as the government of Alberta, to reduce GHG emissions from oil sands production.

Wetlands Impacts

EPA co-administers the Clean Water Act Section 404 regulatory program, which regulates the discharge of dredged or fill material into waters of the United States, including wetlands. While we appreciate that the U.S. Army Corps of Engineers is responsible for day-to-day processing of permit applications, our review of aerial photography recently posted on the Project's website indicates that the DEIS may have underestimated the extent of ecologically valuable bottomland hardwood wetlands in Texas. We appreciate your agreement to evaluate these wetland estimates in the Final EIS and to display the location of the bottomland hardwood wetlands with maps and aerial photography. Given their ecological importance, we recommend the same evaluation be done for prairie pothole wetlands that may be impacted by the proposed Project. EPA also recommends that the Final EIS discuss whether it is possible to make further pipeline route variations to avoid both bottomland hardwood and prairie pothole wetlands.

Our review of the aerial photography also indicates that there may be numerous wetland crossings that would impact more than 0.5 acres of wetlands, which is the upper threshold for impacts under the US Army Corps of Engineers' (Corps) nationwide general permit for utility line crossings in waters of the United States. In that light, and recognizing that there will be several hundred acres of wetlands affected along the entire pipeline route, we recommend that the Corps review the proposed wetland impacts as a single project requiring an individual Clean Water Act Section 404 permit. Consolidating each of these crossings into one individual permit review would also provide for more transparency as to the project impacts and allow for more effective mitigation planning, as well as compliance monitoring of the entire project.

Finally, we appreciate your agreement to provide a discussion of potential mitigation measures for project activities that permanently convert forested wetlands to herbaceous wetlands. We continue to recommend providing a conceptual wetland mitigation plan in the Final EIS, including a monitoring component that would, for a specified period of time, direct field evaluations of those wetlands crossed by the pipeline (and mitigation sites) to ensure wetland functions and values are recovering. We also recommend that the Final EIS evaluate the feasibility of using approved mitigation banks to compensate for wetlands impacts.

Migratory Birds

The SDEIS includes a summary of regulatory and other programs aimed at protecting migratory bird populations that may be affected by oil sands extraction activities in Canada. However, we recommend that the Final EIS provide additional information that would address

potential impacts to specific migratory species, with an emphasis on already-vulnerable species, and we appreciate your agreement to provide that information in the Final EIS. Data found in the North American Breeding Bird Survey (a partnership between the U.S. Geological Survey's Patuxent Wildlife Research Center and the Canadian Wildlife Service's National Wildlife Research Center), which monitors bird populations and provides population trend estimates, should be helpful. We also recommend that the Final EIS discuss mitigation measures that are either currently or could be employed for identified impacts.

Conclusion

Based on our review, we have rated the SDEIS as "Environmental Objections - Insufficient Information (EO-2)" (see enclosed "Summary of Rating Definitions and Follow-up Actions"). As explained in this letter, we have a number of concerns regarding the potential environmental impacts of the proposed Project, as well as the level of analysis and information provided concerning those impacts. Our concerns include the potential impacts to groundwater resources from spills, as well as effects on emission levels at refineries in the Gulf Coast. In addition, we are concerned about levels of GHG emissions associated with the proposed Project, and whether appropriate mitigation measures to reduce these emissions are being considered. Moreover, the SDEIS does not contain sufficient information to fully assess the environmental impacts of the proposed Project, including potential impacts to groundwater resources and communities that could be affected by potential increases in refinery emissions.

We look forward to continuing to work with you to strengthen the environmental analysis of this project and to provide any assistance you may need to prepare the Final EIS. In addition, we will be carefully reviewing the Final EIS to determine if it fully reflects our agreements and that measures to mitigate adverse environmental impacts are fully evaluated. We look forward as well to working with you as you consider the determination as to whether approving the proposed project would be in the national interest under the provisions of Executive Order 13337.

Please feel free to contact me at (202) 564-2400, or have your staff contact Susan Bromm, Director, Office of Federal Activities, at (202) 564-5400, if you have any questions or would like to discuss our comments.

Sincerely,



Cynthia Giles

Enclosure

Summary of Rating Definitions and Follow-up Action

Environmental Impact of the Action

LO--Lack of Objections

The EPA review has not identified any potential environmental impacts requiring substantive changes to the proposal. The review may have disclosed opportunities for application of mitigation measures that could be accomplished with no more than minor changes to the proposal.

EC--Environmental Concerns

The EPA review has identified environmental impacts that should be avoided in order to fully protect the environment. Corrective measures may require changes to the preferred alternative or application of mitigation measures that can reduce the environmental impact. EPA would like to work with the lead agency to reduce these impacts.

EO--Environmental Objections

The EPA review has identified significant environmental impacts that must be avoided in order to provide adequate protection for the environment. Corrective measures may require substantial changes to the preferred alternative or consideration of some other project alternative (including the no action alternative or a new alternative). EPA intends to work with the lead agency to reduce these impacts.

EU--Environmentally Unsatisfactory

The EPA review has identified adverse environmental impacts that are of sufficient magnitude that they are unsatisfactory from the standpoint of public health or welfare or environmental quality. EPA intends to work with the lead agency to reduce these impacts. If the potentially unsatisfactory impacts are not corrected at the final EIS stage, this proposal will be recommended for referral to the CEQ.

Adequacy of the Impact Statement

Category 1--Adequate

EPA believes the draft EIS adequately sets forth the environmental impact(s) of the preferred alternative and those of the alternatives reasonably available to the project or action. No further analysis or data collection is necessary, but the reviewer may suggest the addition of clarifying language or information.

Category 2--Insufficient Information

The draft EIS does not contain sufficient information for EPA to fully assess environmental impacts that should be avoided in order to fully protect the environment, or the EPA reviewer has identified new reasonably available alternatives that are within the spectrum of alternatives analyzed in the draft EIS, which could reduce the environmental impacts of the action. The identified additional information, data, analyses, or discussion should be included in the final EIS.

Category 3--Inadequate

EPA does not believe that the draft EIS adequately assesses potentially significant environmental impacts of the action, or the EPA reviewer has identified new, reasonably available alternatives that are outside of the spectrum of alternatives analyzed in the draft EIS, which should be analyzed in order to reduce the potentially significant environmental impacts. EPA believes that the identified additional information, data, analyses, or discussions are of such a magnitude that they should have full public review at a draft stage. EPA does not believe that the draft EIS is adequate for the purposes of the NEPA and/or Section 309 review, and thus should be formally revised and made available for public comment in a supplemental or revised draft EIS. On the basis of the potential significant impacts involved, this proposal could be a candidate for referral to the CEQ.

Exhibit 14



United States Department of the Interior



BUREAU OF LAND MANAGEMENT

Miles City Field Office

111 Garryowen Road

Miles City, Montana 59301-7000

www.blm.gov/mt

In Reply Refer To:

October 2014 Comp Sale
3160 (MTC023)

May 19, 2014

Dear Reader:

The Bureau of Land Management (BLM) Miles City Field Office has prepared an environmental assessment (EA) to analyze the potential effects from offering 18 nominated lease parcels for competitive oil and gas leasing in a sale tentatively scheduled to occur on October 21, 2014.

The EA with an unsigned Finding of No Significant Impact (FONSI) is available for a 30-day public comment period. Written comments must be postmarked by June 18, 2014, to be considered. Comments may be submitted using one of the following methods:

Email: BLM_MT_Miles_CityFO_Lease_EA@blm.gov

Mail: Miles City Field Office
Attn: Jon David
111 Garryowen Road
Miles City, Montana 59301-7000

Before including your address, phone number, e-mail address, or other personal identifying information in your comment, you should be aware that your entire comment – including your personal identifying information – will be available for public review. If you wish to withhold personal identifying information from public review or disclosure under the Freedom of Information Act (FOIA), you must clearly state, in the first line of your written comment, “CONFIDENTIALITY REQUESTED.” While you can ask us in your comment to withhold your personal identifying information from public review, we cannot guarantee that we will be able to do so. All submissions from organizations, from businesses, and from individuals identifying themselves as representatives of organizations or businesses, will be available for public review.

Upon review and consideration of public comments, the EA will be updated as needed. Based on our analysis, parcels recommended for leasing in our assessment would be included as part of a competitive oil and gas lease sale tentatively scheduled to occur on October 21, 2014.

Prior to issuance of any leases, the Decision Record and FONSI will be finalized and posted for public review on our BLM website. Please refer to the Montana/Dakotas BLM website at

<http://blm.gov/qtld>. Current and updated information about our EAs, Lease Sale Notices, and corresponding information pertaining to this sale can be found at the link referenced above.

If you have any questions or would like more information about lease sale notices or the issuance of the EA, Decision Record and FONSI, please contact me at 406-233-2837.

Sincerely,

A handwritten signature in black ink, appearing to read "Todd D. Yeager". The signature is stylized with a large, sweeping initial "T" and a long, horizontal stroke extending to the right.

Todd D. Yeager
Field Manager

United States Department of the Interior
Bureau of Land Management

Environmental Assessment DOI-BLM-MT-C020-2014-0091-EA
May 19, 2014

Project Title: Oil and Gas Lease Parcel, October 21, 2014 Sale

Location: Miles City Field Office (see Appendix A for list of lease parcels by number and legal description and Maps 1-6)



Miles City Oil and Gas Lease Sale EA
DOI-BLM-MT-C020-2014-0091-EA

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4.3.20.1 Social

4.3.20.1.1 Direct and Indirect Effects

Leasing the parcels would have no direct impacts on social resources. Any potential effects from the sale of leases could occur at the time the leases are developed.

While the act of leasing Federal minerals itself would result in no social impact, subsequent exploration and development may generate impacts to people living near or using the area in the vicinity of the lease. Exploration, drilling or production could create an inconvenience to people living adjacent to leases due to increased traffic and traffic delays, and light, noise and visual impacts. This could be especially noticeable in rural areas where oil and gas development has not occurred previously. The amount of inconvenience would depend of the activity affected, traffic patterns within the area, noise and light levels, length of time and season these activities occur, etc. In addition, competition for housing could occur in some communities. However, residents living in areas that have been experiencing ongoing population losses may support the increased employment and population related to oil and gas development. Residents of counties where the development actually occurs would also benefit from the additional revenues to counties due to oil and gas leasing and development.

There is potential for disproportionate effects to low income or minority populations, specifically American Indian populations. Consultation with potentially affected Tribes would occur at the APD stage.

4.3.20.2 Economics

4.3.20.2.1 Direct and Indirect Effects

Under Alternative B, 18 parcels in counties would be made available for leasing at the October 2014 lease auction. The leasing of an additional 7,945 acres of BLM administered minerals in these counties would generate additional public revenue, stimulate economic activity, and boost production associated with Federal minerals. It is estimated that the leasing of all minerals nominated for the October auction would generate more than \$756,000 in one-time bonus bids and \$14,000 annually in rent revenue for the Federal government. Forty-nine percent of Federal revenue collected from public domain minerals and 25 percent of Federal revenue from acquired minerals (acquired under Bankhead Jones authority) are redistributed to the State. Montana then distributes 25 percent of public domain revenue and all of acquired mineral revenue back to the counties where the leases exist. Approximately 94 percent of federal minerals leased by the BLM within McCone, Powder River, Prairie, Richland and Roosevelt counties are public domain minerals. If these additional parcels were to be leased, an additional \$43,000 would be paid to the State of Montana and the five counties would receive an additional \$12,000 from the redistribution of federal revenue.

Once oil and gas extraction begins, annual rent payments on leased minerals stops and lessees begin to pay royalties equal to 12.5 percent of the value of production (43 CFR 3103.3.1). Royalties associated with future development of nominated minerals is estimated to generate an additional \$206,000 annually in federal oil and gas royalties. Of this new federal revenue, an estimated \$98,000 could be disbursed to the State and \$27,000 is estimated to be redistributed back to the five counties.

In addition to generating additional public revenue, leasing an additional 7,945 acres of federal minerals in McCone, Powder River, Prairie, Richland and Roosevelt counties will stimulate economic activity in the private sector of the local 8-county economy. Increased local demand for oil and gas drilling and support activities will create a ripple effect in the local economy as new employment and income opportunities in oil and gas related industries indirectly creates opportunities in nearly all other sectors of the local economy.

The total economic impact of leasing activities proposed under Alternative B is equal to direct and indirect effects of drilling activities, as well as the direct and indirect effects of additional public revenue redistributed back to the five counties. As shown in Table 14, the bonus bids, rents, royalties, and drilling and support activities associated with leasing an additional 7,945 acres of federal minerals is estimated to support 2 additional jobs and \$61,000 in labor income across the 8-county local economy (IMPLAN, 2014).

Disclosure of the direct, indirect, and cumulative effects of GHG emissions provides information on the potential economic effects of climate change including effects that could be termed the “social cost of carbon” (SCC). The EPA and other federal agencies developed a method for estimating the SCC and a range of estimated values (EPA 2014). The SCC estimates damages associated with climate change impacts to net agricultural productivity, human health, property damage, and ecosystems. Using a 3 percent average discount rate and year 2020 values, the incremental SCC is estimated to be \$46 per metric ton of annual CO₂e increase. Based on the GHG emission estimate provided in Section 4.3.3.1.2, the annual SCC associated with potential development on lease sale parcels is \$38,499 (in 2011 dollars). Estimated SCC is not directly comparable to economic contributions reported above, which recognize certain economic contributions to the local area and governmental agencies but do not include all contributions to private entities at the regional and national scale. Direct comparison of SCC to the economic contributions reported above is also not appropriate because costs associated with climate change are borne by many different entities.

4.3.21 Cumulative Impacts- Alternative B

Cumulative impacts are those impacts resulting from the incremental impact of an action when added to other past, present, and reasonably foreseeable actions regardless of what agency or person undertakes such other actions (40 CFR 1508.7). This section describes cumulative impacts associated with this project on resources. The ability to assess the potential cumulative impacts at the leasing stage for this project is limited for many resources due to the lack of site-specific information for potential future activities. Upon receipt of an APD for any of the lease parcels addressed in this document, more site-specific planning would be conducted in which the ability to assess contributions to cumulative impacts in a more detailed manner would be greater due to the availability of more refined site-specific information about proposed activities.

4.3.21.1 Past, Present and Reasonably Foreseeable Future Actions

Past, present, or reasonably foreseeable future actions that affect the same components of the environment as the Proposed Action are: grazing, roads, wildfire and prescribed fire, range improvement projects, and utility rights-of-way.

Exhibit 15

EXHIBIT 35

**U.S. Department of the Interior
Bureau of Land Management**

**Environmental Assessment
DOI-BLM-ID-B010-2014-0036-EA**

**Little Willow Creek
Protective Oil and Gas Leasing**

February 10, 2015

U.S. Department of the Interior
Bureau of Land Management
Four Rivers Field Office
3948 Development Avenue
Boise, ID 83705



Environmental Assessment # DOI-BLM-ID-B010-2014-0036-EA
Little Willow Creek Protective Oil and Gas Leasing

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Environmental Assessment # DOI-BLM-ID-B010-2014-0036-EA
Little Willow Creek Protective Oil and Gas Lease

1.0 Introduction

Leasing

The Mining and Minerals Policy Act of 1970 declares that it is the continuing policy of the Federal Government to foster and encourage private enterprise in the development of a stable domestic minerals industry and the orderly and economic development of domestic mineral resources. The Mineral Leasing Act of 1920, as amended, authorizes the Secretary of the Interior to lease federal oil and gas. The Bureau of Land Management (BLM) is the Interior agency delegated the authority to manage the United States' mineral resources. The BLM's oil and gas leasing programs are codified under 43 CFR 3100, in accordance with the authority of the Mineral Leasing Act of 1920, as amended, the Federal Land Policy and Management Act (FLPMA) of 1976, and the Energy Policy Act of 2005.

The decision as to which public lands and minerals are open for leasing and what leasing stipulations may be necessary is made during the land use planning process. Surface management/use for mineral extraction on non-BLM administered land overlaying federal minerals will be determined by the BLM in consultation with the appropriate surface management agency or the private surface owner at the time such surface use is proposed by the leaseholder or designated agent. Under the Mineral Lease Act, issuing oil and gas leases is a discretionary authority conveyed to the Secretary of Interior. In carrying out the mineral leasing authority conveyed through the Mineral Leasing Act, the BLM must comply with other applicable federal laws and regulations, including, but not limited to the Endangered Species Act, the National Historic Preservation Act, the Clean Water Act, the Clean Air Act, and the Energy Policy Act.

Offering federal mineral estate parcels for lease and subsequently issuing oil and gas leases are strictly administrative actions, which, in and of themselves, do not cause or directly result in any surface disturbance. Issuance of an oil and gas lease does convey to the lessee the exclusive right to use as much of the leased land as is reasonably necessary to explore for and extract oil and gas resources from the lease area, subject to the terms of the lease, including stipulations (43 CFR 3101.1-2 and 3101.1-3), regulations pertaining to oil and gas leasing, Onshore Orders, and with prior approval of the Authorized Officer. However, depending on lease stipulations, post-leasing activities may or may not result in impacts to surface resources. Only where stipulations or conditions do not preclude disturbance to surface resources is the action considered an irretrievable commitment of resources. The BLM may issue leases to protect the public interest when uncompensated drainage is occurring or may occur, provided the lease does not convey an irreversible or irretrievable commitment of resources.

As part of the lease issuance process, nominated parcels are reviewed against the appropriate land use plan, and stipulations are attached to mitigate any known environmental or resource conflicts that may occur on a given lease parcel. As stated above, on-the-ground impacts would potentially occur when a lessee applies for and receives approval to explore, occupy and/or drill

Leasing - Federal oil and gas leases generate a one-time lease bid as well as annual rents. Parcels containing federal minerals, which have been approved for leasing, are auctioned off periodically to interested parties starting at a minimum bid of \$2.00 per acre. Many parcels leased at auction generate bonus bids in excess of the minimum bid. In 2014, bonus bids ranged from \$50.24/acre (October) to \$79.68/acre (January) for State leases; however, because no leases have been offered, figures for federal minerals are not available. Once federal minerals are leased, leases are subject to annual rent or royalty payments. Rent on leased minerals is \$1.50 per acre per year for the first five years and \$2.00 per acre per year thereafter. Typically, oil and gas leases expire after 10 years unless drilling activity on these parcels results in one or more producing wells.

Production – Idaho currently has one producing well on private land and none associated with federal mineral estate (IPAA 2012, IDL 2014). Of 18 Payette County gas wells currently permitted by IDL, one is in production, 10 have been drilled and are shut pending a pipeline (Table 11). Once production begins, federally leased minerals are considered to be held by production and lease holders are required to pay royalties on production instead of annual rent. The BLM also considers mineral leases to be held by production if they have been incorporated into fields or units working cooperatively to increase extraction capabilities.

Federal oil and gas production is subject to production taxes or royalties. On public domain lands, these federal oil and gas royalties generally equal 12.5% of the value of production (43 CFR 3103.3.1), of which 50% would be allocated to the State and 50% would be allocated to the U.S. Treasury. In Idaho, 90% of federal mineral royalty revenues that the state receives are distributed to the Public School Income Fund and 10% distributed to the general fund of the counties where the revenue was generated. For State leases, a 12.5% production royalty is distributed to the permanent fund of the appropriate beneficiary, other State agencies, and the General Fund. The 2.5% production tax goes to the producing county (11.2% of tax revenue), cities within the producing county (11.2%), public schools (11.2%), local economic development (6.4%), and an oil and gas conservation fund (60%).

Local Economic Contribution - Oil and gas development has the potential to stimulate economic activity in a number of sectors throughout the region. Exploration, development, and production activities create a multiplier effect in the local economy as money spent in the oil and gas related industries is spent and re-spent in other industries (Table 12).

3.14.2 Environmental Consequences – Social and Economic

Impacts to the social and economic environment are based on the RFDS created for this document (Table 2, Appendix 1).

3.14.2.1 General Discussion of Impacts

Social and Environmental Justice

Development of a lease may generate impacts to people living near or using the area in the vicinity of the lease. Oil and gas exploration, drilling, or production could create an inconvenience to these people due to increased traffic and traffic delays, noise, and visual impacts. This could be especially noticeable in areas where oil and gas development has been

minimal. The amount of inconvenience would depend on the activity affected, traffic patterns within the area, noise levels, length of time, and season these activities occurred, etc. Creation of new access roads into an area could allow increased public access and exposure of private property to vandalism. For split estate leases, surface owner agreements, standard lease stipulations, and BMPs could address many of the concerns of private surface owners. Production and development activities could disproportionately affect disadvantaged groups where the activities are specifically targeted to their communities or properties to the benefit or avoidance of non-disadvantaged groups. They could also provide job opportunities for those groups.

Economics

Local and/or out-of-state workers could be hired or contracted to meet the direct and indirect needs of development and production. Individual income for workers typically associated with development and production activities would vary from \$8,300 to \$94,500 annually (Table 12). Mining-related jobs would likely pay above the median income (\$32,400/year). Total new jobs created could be relatively low because some work would be short-term in nature. For each million dollars in gas production, 2.4 jobs could be created in the county of production (Weber 2012). Employees may shift to higher paying energy-related jobs creating a labor shortage for local employers. Sudden influxes of workers could reduce affordable housing availability. An influx of workers and equipment without commensurate financial support could adversely affect public and private sector infrastructure (schools, hospitals, law enforcement, fire protection, and other community needs), especially in rural communities. Tax, royalty, spending, and income revenues associated with leasing, development, and production would benefit local, county, State, and national economies. Stipulations that affect access to mineral resources could reduce economic return for lessors and lessees. Activities that increase access to mineral resources could benefit other mineral rights holders. Activities that adversely affect health, safety, or the environment could cause short- or long-term decreases in personal income and property values. Wildlife depredation on agricultural fields could adversely affect productivity of some crops (e.g., winter wheat, alfalfa).

Disclosure of the direct, indirect, and cumulative effects of GHG emissions provides information on the potential economic effects of climate change including effects that could be termed the “social cost of carbon” (SCC). The EPA and other federal agencies developed a method for estimating the SCC and a range of estimated values (EPA 2014). The SCC estimates damages associated with climate change impacts to net agricultural productivity, human health, property damage, and ecosystems. Using a 3% average discount rate and year 2020 values, the incremental SCC is estimated to be \$51 per ton of annual CO₂eq increase.

3.14.2.2 Alternative A

Social and Environmental Justice

Not leasing the federal mineral estate in the project area would limit the development potential of the project area to only two wells, both located on private lands. Developing two wells and associated infrastructure would have minor short-term impacts from increased traffic and noise and long-term visual, public access, and vandalism impacts. Limited increases in access and

worker influx would occur. There are disadvantaged groups in Payette County, but they do not appear to be disproportionately associated with the two wells or the proposed lease area.

Economics

By not leasing, federal, state, or local revenues would not be generated from leasing, rents, or royalties from federal mineral estate. If BLM does not lease the federal minerals, it is likely that the IOGCC would allow the federal mineral estate to be omitted from the drilling unit. Moderate (if 493 acres associated with existing wells are omitted) to major (if up to 6,349 acres throughout the lease area are omitted) resource and revenue losses would occur if the IOGCC omitted the federal mineral estate and productive wells are drilled on private lands in the same unit. Development and production of two wells would cause minor employment and income increases. Negligible to minor impacts to labor and housing availability and infrastructure would occur over the short term. Adjacent mineral rights holders would experience minor beneficial (omission allowed) or moderate adverse (omission not granted) financial impacts. Adverse water quality and availability (Section 3.5.2.2), safety, and environmental impacts would primarily affect individual landowners in the immediate vicinity of the wells. Negligible wildlife depredation losses could occur.

Based on the GHG emission estimate (Table 6), the annual SCC associated with two wells would be \$295,137 (in 2011 dollars). Estimated SCC is not directly comparable to economic contributions reported above, which recognize certain economic contributions to the local area and governmental agencies, but do not include all contributions to private entities at the regional and national scale. Direct comparison of SCC to the economic contributions reported above is also not appropriate because costs associated with climate change are borne by many different entities.

3.14.2.3 Alternative B

Social and Environmental Justice

Developing 22 wells and associated infrastructure would have moderate to major short-term increased traffic and noise impacts and long-term visual impacts. Minor (access controlled by private landowners) to major (access not controlled by private landowners) access and vandalism impacts could occur over the long term. A moderate worker influx could adversely affect traditional lifestyles. Disadvantaged groups in Payette County would not be directly affected by the wells, but access to affordable housing and social services in nearby communities could be reduced during the short term.

Economics

Federal, state, or local revenues would be generated from leasing and rents (\$9,528 to \$12,704 annually) during the 10-year lease period. The NSO and NSSO stipulations could reduce the lease value and bonus bid amounts. Developing and maintaining 22 wells would have minor to moderate short-term and negligible long-term job increases. Royalty income would depend on how productive the wells are and cannot be estimated at this time. Minor to moderate impacts to labor and housing availability and infrastructure would occur over the short term. Adjacent mineral rights holders would experience moderate financial benefits where access to their minerals improved. Adverse water quality and availability (Section 3.5.2.3), safety, and

environmental impacts could have negligible (wells remain intact and don't affect ground water) to major (surface and ground water adversely affected by multiple wells) to the adjacent landowners and downstream communities. Minor to moderate wildlife depredation losses could occur. Based on the GHG emission estimate (Table 6), the annual SCC associated with 22 wells would be \$3,246,711 (in 2011 dollars).

3.14.2.4 Alternative C

Social and Environmental Justice

The impacts of developing 25 wells and associated infrastructure would be as described in Alternative B (Section 3.14.2.3).

Economics

Leasing 6,349 acres and associated development and production would have similar revenue, job, labor and housing availability, infrastructure, and adjacent mineral rights holder impacts as described in Alternative B (Section 3.14.2.3). The impact of CSU stipulations on lease value would be less than Alternative B and royalty income could be greater. Adverse water quality and availability (Section 3.5.2.4), safety, and environmental impacts would be similar to Alternative B; however, the freshwater aquatic habitat CSU stipulation could provide minor to moderate surface water protection. Minor wildlife depredation losses could occur. Based on the GHG emission estimate (Table 6), the annual SCC associated with 25 wells would be \$3,689,442 (in 2011 dollars).

3.14.3 Mitigation

Measures that limit or control dust, noise, odors and protect visual impacts and water quality resources would help reduce social and economic impacts (Dahl et. al. 2010).

3.14.4 Cumulative Impacts – Social and Economic

Cumulative impacts to the social and economic environment are based on the RFDS created for this document (Table 2, Appendix 1), RFDS for the Willow and Hamilton fields, and the activities identified below.

3.14.4.1 Scope of Analysis

Payette County will serve as the CIAA. Although social and economic costs and benefits could occur at regional, state, national, and international levels, the majority would occur at the county level. The lease period of 10 years will be used for the temporal analysis limit because the federal mineral estate would be available for production during that time period, but not necessarily beyond.

3.14.4.2 Current Conditions and Effects of Past and Present Actions

Current Payette County social and economic conditions are described in Section 3.14.1. All State-owned minerals (Section 3.13.1) and an unknown acreage of privately-owned minerals have been leased in recent years. The State leases will expire between 2016 (14,181 acres) and 2024. The existing 17 oil and gas wells have been developed over several years, although the

Exhibit 16



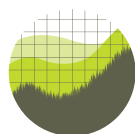
OMITTED DAMAGES:

What's Missing From the Social Cost of Carbon

March 13, 2014

Peter Howard

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Institute for
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new york university school of law



The Cost of Carbon Project is a joint project of the Environmental Defense Fund, the Institute for Policy Integrity, and the Natural Resources Defense Council.



ABSTRACT

The 2013 Interagency Working Group on the Social Cost of Carbon (IWG) updated the U.S. social cost of carbon (SCC) for 2015 from a central value of \$24 to \$37 using three integrated assessment models (IAMs): DICE-2010, FUND 3.8, and PAGE09. The SCC is the additional economic damage caused by one ton of carbon dioxide. While some have questioned the increase in the SCC as too high, a thorough examination of the latest scientific and economic research shows that \$37 should be viewed as a lower bound. This is because the studies available to estimate the SCC omit many climate impacts—effectively valuing them at zero. Where estimates are available for a given type of impact, they tend to include only a portion of potential harms. This paper represents the first attempt to systematically examine and document these omissions for the latest versions of the three IAMs used by the IWG, as well as earlier versions when they are used in calibrating the updated models.

The table on the following page summarizes hot spot damages including increases in forced migration, social and political conflict, and violence; weather variability and extreme weather events; and declining growth rates. A better accounting of catastrophic damages is also needed, as well as many other impacts.

While there is a downward bias to the U.S. SCC estimates due to these omissions, the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates, as measuring at least some of the costs of carbon dioxide is better than assuming they are zero. At the same time, the OMB should more thoroughly document downward biases of the current U.S. SCC estimates, potentially using this report to list in detail all of the currently omitted damages.

Missing or Poorly Quantified Damages Needed to Improve SCC Models*

General Impact	Category	Pages
Health	Respiratory illness from increased ozone pollution, pollen, and wildfire smoke	30
	Lyme disease	30
	Death, injuries, and illnesses from omitted natural disasters and mass migration	30
	Water, food, sanitation, and shelter	30
Agriculture	Weeds, pests and pathogens	20
	Food price spikes	Note 83
	Heat and precipitation extremes	41
Oceans	Acidification, temperature, and extreme weather impacts on fisheries, species extinction and migration, and coral reefs	18-20, 41-42
	Storm surge interaction with sea level rise	37-38
Forests	Ecosystem changes such as pest infestations and pathogens, species invasion and migration, flooding and soil erosion	20
	Wildfire, including acreage burned, public health impacts from smoke pollution, property losses, and fire management costs (including injuries and deaths)	20, 30
Ecosystems	Biodiversity**, habitat**, and species extinction**	29
	Outdoor recreation** and tourism	23
	Ecosystem services**	27-28
	Rising value of ecosystems due to increased scarcity	31-32
	Accelerated decline due to mass migration	34

General Impact	Category	Pages
Productivity and economic growth	Impacts on labor productivity and supply from extreme heat and weather, and multiple public health impacts across different damage categories	24-25
	Impacts on infrastructure and capital productivity and supply from damages from extreme weather events and infrastructure and diversion of financial resources toward climate adaptation	25
	Impact on research and development from diversion of financial resources toward climate adaptation	25
Water	Availability and competing needs for energy production, sanitation, and other uses	21, 41
	Flooding	41
Transportation	Changes in land and ocean transportation	21-22
Energy	Energy supply disruptions	21
Catastrophic impacts and tipping points**	Rapid sea level rise**	8, 36
	Methane releases from permafrost**	8, 36
	Damages at very high temperatures***	Note 23
	Unknown catastrophic events	36-37
Inter- and intra-regional conflict	National security	39, 41
	Increased violent conflicts from refugee migration from extreme weather, and food, water and land scarcity	34-35

*This table catalogues climate impacts that have been largely unquantified in the economics literature and are therefore largely omitted from SCC models. Quantified impacts represented in the models include: changes in energy (via cooling and heating) demand; changes in agricultural and forestry output from changes in average temperature and precipitation levels, and CO₂ fertilization; property lost to sea level rise; coastal storms; heat-related illnesses; and some diseases (e.g. malaria and dengue fever).

** These impacts are represented in a limited way in one or more of the SCC models: 1) they may be Included in some models, and not others; 2) they may be included only partially (e.g., only one or several impacts of many in the category are estimated); 3) they may be estimated using only general terms not specific to any one damage—in these instances, estimated damages are usually very small relative to their potential magnitude, and relative to the impacts explicitly estimated in the models. See complete report for details.

*** While technically represented in SCC models through extrapolations from small temperature changes, there are no available climate damage estimates for large temperature changes, and these may be catastrophic.

OMITTED DAMAGES:

What's Missing From the Social Cost of Carbon⁺

Peter Howard*

In 2008, the United States Court of Appeals for the Ninth Circuit ruled that executive branch agencies must include the climate benefits of a significant regulatory action in federal benefit-cost analyses (BCA) to comply with Executive Order 12,866. In response, an Interagency Working Group on the Social Cost of Carbon was formed in 2010 to develop a consistent and defensible estimate of the social cost of carbon (SCC) using models drawn from the literature (Masur and Posner 2011). The SCC is the global cost to all future generations from one additional unit of carbon pollution in a given time period; forest fires, drought, and disease are just some of the costly consequences of climate change that are ideally included within it.¹ Thus, the SCC captures the benefit of reduced carbon pollution from a policy in terms of expenses avoided.

The SCC is estimated using Integrated Assessment Models (IAMs), which integrate a simplified climate model and a simplified economic model into a cohesive numerical model to capture the feedback effects between the two.² Using a methodology specified in the 2010 Technical Support Document (IWG, 2010), the 2010 Interagency Working Group developed a central estimate (corresponding to a constant discount rate of 3 percent) of \$24 for a 2015 emission of carbon using three Integrated Assessment Models (IAMs): DICE-2007 (Nordhaus 2008), FUND 3.5 (Anthoff and Tol 2010), and PAGE2002 (Hope 2006). Using an identical methodology and updated versions of these three models—DICE-2010 (Nordhaus 2010), FUND 3.8 (Anthoff and Tol 2012),³ and PAGE09 (Hope 2011)—the 2013 IWG re-estimated the central SCC estimate at \$37 in 2015.⁴ See Tables 1-3 for a full comparison of the 2010 and 2013 SCC estimates.

With its release by the 2013 Interagency Working Group on the Social Cost of Carbon (IWG), the U.S. government's updated social cost of carbon estimate catapulted into the national political debate. This surge in interest is mostly the result of the approximately 54 percent increase in the federal government's central 2015 SCC estimate from 2010 to 2013. Because the 2013 IWG used the same methodology to estimate the global SCC as the 2010 IWG (IWG 2013),⁵ all changes in the SCC estimates are the result of updates to the three IAMs used for estimation. Regardless, considerable debate has ensued due to the significant implication this increase has on current and future U.S. policies.

While some conservative politicians and industry groups question the increase saying it is too high, this report shows more generally that, if anything, these SCC estimates are biased downward, probably significantly so. This downward bias is the result of modeling decisions by the 2010 IWG and modeling decisions by the authors of the current IAMS, including the use of outdated damage estimates and the omission of several climate

* Peter Howard is an Economic Fellow at the Institute for Policy Integrity at the New York University School of Law. This position is jointly funded by Environmental Defense Fund, Natural Resources Defense Council, and Policy Integrity.

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change impacts. This report focuses primarily on omitted damages due to the likelihood that their inclusion would have a significant effect on the SCC.⁶ These omissions include climate impacts on the following market sectors: agriculture, forestry, and fisheries (including pests, pathogens, and weeds, erosion, fires, and ocean acidification); ecosystem services (including biodiversity and habitat loss); health impacts (including Lyme disease and respiratory illness from increased ozone pollution, pollen, and wildfire smoke); inter-regional damages (including migration of human and economic capital); inter-sector damages (including the combined surge effects of stronger storms and rising sea levels), exacerbation of existing non-climate stresses (including the combined effect of the over pumping of groundwater and climate-driven reductions in regional water supplies); socially contingent damages (including increases in violence and other social conflict); decreasing growth rates (including decreases in labor productivity and increases in capital depreciation); weather variability (including increased drought and in-land flooding); and catastrophic impacts (including unknown unknowns on the scale of the rapid melting of Arctic permafrost or ice sheets).

Despite these downward biases to federal SCC estimates, this report argues that the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates; they are underestimates, but we should, at a minimum, count the damages we can. At the same time, the OMB should emphasize more strongly the downward bias of the current SCC estimates and commit to addressing this bias in future updates of the estimates.

This report focuses on identifying the important categories of harm from climate change that are omitted from current IAMs. We first review the general categories of climate damages. Second, we describe how the latest versions of the three IAMs (DICE-2013, FUND 3.6, and PAGE09) are calibrated.⁷ Third, we discuss a frequent cause of omitting damages: a lack of sound damage estimate(s) in the literature resulting from scientific and economic uncertainty in determining the magnitude of the effect. Fourth, using the previous two sections as a basis, we discuss the important categories of damages that are omitted. Fifth, we discuss the treatment of adaptation in these models, and whether omitted damages are likely to be incurred. Finally, we conclude with a discussion of the findings and what our results imply for the future estimation of climate damages.

DAMAGES

The rising temperatures and ecological shifts brought on by global climate change are expected to affect myriad aspects of natural ecosystems and human civilization. Though climate change may create benefits in some regions and sectors, the long-term effects of climate change are projected to be overwhelmingly negative. To help policymakers weigh the costs of climate mitigation and adaptation, these impacts are monetized by economists as damages. Damages can be broadly segmented into market damages, which manifest as a loss of gross domestic product (GDP) and non-market damages, which manifest in terms of lost welfare. Damages also include shocks to political stability, massive ecological regime changes (such as tipping points and mass species extinction), and impediments to sustained economic growth, none of which are easily predicted or quantified (U.S. Climate Change Science Program, 2008; Yohe and Tirpak 2008).

Market Damages

Market damages refer to changes in welfare due to changes in income or the availability, quality, or price of a market commodity or input. Most market damages result from shifts in productivity and a corresponding shift

in output and GDP. Market damages can also be the result of the loss or depreciation of capital such as land or infrastructure (Goulder and Pizer 2006; Mendelsohn 2003).⁸

Sectors in which market damages from climate change are forecast include agriculture, due to increased temperatures, CO₂ fertilization, changing rainfall patterns, pests, and pathogens; energy demand, largely due to the increased cost of space cooling and the decreased cost of space heating associated with global temperature rise; energy supply, due to changing energy supply costs (such as increasing power plant cooling costs) and extreme weather energy supply interruptions; transportation and communication, due to delays and infrastructure losses from extreme weather events; forestry, due to shifting suitable habitat ranges, pests, pathogens, and fires; fisheries, due to higher water temperatures, invasive species, and ocean acidification; and water resources, due to increased evaporation rates and changing rainfall patterns. Market damages in the form of land, property, and infrastructure loss and degradation are also expected as a result of sea level rise and extreme weather events. While health damages have market (for example, labor availability and increased healthcare costs) and non-market (such as suffering and the value of human life) aspects, the market damages from health are relatively small compared the non-market damages because households place a high value on human life (Tol 2009; Jorgenson et al., 2004).⁹

In some of these market sectors, climate change is projected to create a net benefit in some countries for low-level temperature increases. For example, increased temperature will increase agricultural and forestry productivity in some regions and increased CO₂ concentrations can improve the nutritional value of soil (via the CO₂ fertilization effect). In some models, the benefits in some sectors are significant enough to result in initial net benefits to the globe from climate change. These sector benefits and the resulting global net benefits, however, are expected to be short-lived as temperatures continue to rise (Warren et al., 2006; Jorgenson et al., 2004). While Tol (2009) finds evidence of net global benefits from climate change up to a 2.2 degrees Celsius increase in temperature, this threshold differs between the three IAMs and even within variants of the same IAM.¹⁰ Some IAMs, such as many of the more recent variants of DICE, find no such evidence of initial benefits.¹¹

Non-market Damages

Non-market damages refer to damages affecting goods or services for which no established market exists, but which still provide value to humans. These non-market goods and services, also referred to as non-market commodities, can generally be thought of as environmental good and services (such as ecosystem services). Environmental goods can be divided into use values, including direct-use values (for example, the pharmaceutical value of biodiversity) and indirect use values (such as the values of ecosystem, recreational, and aesthetic services), and non-use value (including existence, bequest, option, and altruistic values). Another way to subdivide non-market damages is into tangible damages, which by definition can be valued, and intangible damages, which by definition are extremely difficult to value given current methods. While economists have established valuation techniques for tangible damages, the accuracy of these estimates vary by the type of good and service. For example, use values, particularly direct-use values, are more easily quantified than non-use values.¹²

Projected damages to non-market goods from climate change that are included in one or more IAM include the loss of species and habitat, increases in rates of human mortality and morbidity, and changes in amenity values (that is, the direct welfare change from a more or less hospitable climate) (Anthoff and Tol 2012; Warren et al., 2006; Smith et al., 2003). All tangible damages from climate change are not included in IAMs, such as the

medical value of biodiversity. Intangible benefits, including larger societal implications of climate change, have yet to be meaningfully addressed or incorporated into IAMs (Yohe and Tirpak 2008).

Socially Contingent Damages

Socially contingent damages are damages that result from changes in social dynamics due to climate change. Warmer temperatures, sea level rise, and changing water availability can affect how societies function. For example, mass migration will become more likely as some regions become more inhospitable. Similarly, interpersonal violence and social and political conflict will rise with increased food, water, and resource scarcity. The values of social dynamics are, in most cases, intangible (that is, unmeasured) given current valuation methods; it is difficult to quantify the social effect, let alone value it. As a consequence, socially contingent damages from climate change are almost completely excluded from IAMs.

Catastrophic Impacts

One of the most concerning aspects of climate change is the potential for catastrophic damages. Catastrophic damages are characterized as low probability-high damage events. These damages come from

- tipping points (also known as discontinuities)—“an environmental threshold over which small changes in the environmental state can cause rapid, frequently irreversible changes in ecosystem characteristics” (EDF, NRDC, Policy Integrity, and UCS comments, 2013);
- fat tails—uncertainty in the underlying economic and environmental parameters in IAMs that result in underlying “fat-tailed” distributions, which are distributions (often right skewed) characterized by an extended and fat tail on the upper end of the distribution relative to the normal (bell curve) distribution; and
- black swan events—(that is, unknown unknowns) that refer to currently unknown tipping points or parameter distributions.

While tipping points, fat tails, and black swan events are distinct concepts, they are overlapping issues; this is discussed further below. Furthermore, while IAMs often categorize catastrophic damages as a distinct type of damage from the previous three, they should actually be thought of as damages to market goods, non-market goods and services, and society via cataclysmic climate events—often thought of in this case as rapid and/or extreme climate change.

Catastrophic impacts are often cited as a key reason for immediate action on climate change. Using PAGE09, Hope (2013) demonstrates that tipping point damages, the first of these three types of damages, alone can be as important as economic damages in determining the social cost of carbon.

TIPPING POINTS. As mentioned above, an ecological tipping point is broadly defined as a threshold beyond which a small change in conditions causes rapid, often irreversible changes in ecosystem characteristics. Tipping points are generally more common in intricate systems with many interacting parts, such that even small changes in the system can potentially have large impacts through a snowball effect.¹³ A simple but illustrative example of an ecological tipping point is the effect of deforestation in tropical rainforests. The large trees in the rainforest depend upon nutrient-rich topsoil to thrive. That topsoil is held in place by the root network of the plants it supports and can take centuries to accumulate. The removal of trees accelerates the rate of



Crowning fire in spruce forest. Photo: Murphy Karen, U.S. Fish and Wildlife Service

topsoil erosion while topsoil erosion impedes tree survival rates. Deforestation, then, creates a chicken-and-egg conundrum as reforestation efforts are doomed by a lack of topsoil and topsoil cannot be sustained without an established root network (Brahic 2009).

Within the context of climate change, a tipping point generally refers to a temperature or CO₂ concentration threshold beyond which (even by small perturbations) the future state of Earth's climate system is significantly and irreversibly altered. In other words, a tipping point is an abrupt change in the climate system between stable climate states at the regional scale (at the subcontinental scale or higher) or global scale (Overpeck and Cole 2006). Beyond the temperature or CO₂ concentration threshold that causes this abrupt change, ecological changes would be irreversible on human time scales even if temperature could be returned to pre-threshold levels (Overpeck and Cole 2006; Lemoine and Traeger 2011).

A global tipping point would likely be driven by a series of region-specific or system-specific tipping points (that is, tipping elements), which, taken collectively, would dramatically reduce the Earth's natural capacity to withstand climate change. Lenton et al., (2008) identifies the following tipping elements:

- Arctic sea-ice (decreased areal extent),
- Greenland ice sheet (decreased ice volume),
- West Antarctic ice sheet (decreased ice volume),
- Atlantic thermohaline circulation (decreased overturning),
- El Niño-southern oscillation (increased amplitude),
- Indian summer monsoon (decreased rainfall),
- Sahara/Sahel and West African monsoon (increased vegetation fraction),
- Amazon rainforest (decreased tree fraction), and
- boreal forest (decreased tree fraction).¹⁴

The probability and damages of tipping point scenarios are poorly understood (Weitzman 2011). Due to the considerable uncertainty surrounding these events, some IAMs exclude them altogether. This will be discussed later.

Tipping point damages can be modeled either explicitly or implicitly. If tipping point damages are modeled explicitly, the damages from the crossing of tipping points are modeled using an additional damage function (for example, Hope 2002; Hope 2009; Nordhaus and Boyer 2000; Nordhaus 2008). If tipping point damages are implicitly modeled, tipping points are modeled in IAMs through the choice of climate parameters, specifically the probability distribution functions that represent them, as in Lemoine and Traeger (2011), Weitzman (2009), and Anthoff and Tol (2013a).¹⁵ In this case, tipping point damages are implicitly captured through assumed increases in market and non-market damages resulting from higher temperature from crossing climate tipping point.

Fat Tails. Fat tails refer to the upper ends (that is, the right sides) of the probability density functions of a range of climate change-related variables. Tail fatness is an indicator of how quickly the probability of an event declines relative to the severity of that event, with fatter tails corresponding to lower rates of decline.¹⁶

Martin Weitzman has argued that existing climate models fail to adequately account for the extreme risks of climate change. In Weitzman's eyes, prevailing "structural uncertainties" (that is, unknown unknowns) abound in the economics of climate change, and existing benefit-cost analyses (BCAs) and IAMs have yet to deal adequately with these uncertainties. While IAM modelers often choose thin tailed distributions (for example, the uniform distribution) and medium-tailed distributions (for example, the normal distribution) to represent uncertain climate variables, Weitzman argues that fat-tailed distributions (for example, Student-t-distribution) are more appropriate due to these structural uncertainties in climate change (that is, unknown unknowns) and the "unlimited" potential for the scale of damages (Weitzman 2011).¹⁷ Fat tails arise due to the finite amount of information on catastrophic impacts (due to their rarity in historical record keeping) forcing analysts to specify probability distribution functions of probability distribution functions. In other words, Weitzman believes that existing IAMs and BCAs under account for the potential of extreme, irreversible impacts of climate change by assuming thin-tailed and medium-tailed distribution functions,¹⁸ which render the likelihood of extreme damages from climate change small enough to write off (Weitzman 2009; Nordhaus 2012).

Weitzman (2011) identifies multiple sources of structural uncertainty in existing climate modeling literature and models; he emphasizes that these sources are not exhaustive, and more likely exist. The five structural uncertainties that he identifies are: (1) the unprecedented rate and scope of increases in atmospheric greenhouse gas (GHG) concentrations, (2) the uncertainty surrounding the response of global temperatures to this dramatic increase in GHG emissions, (3) the potential for positive feedback mechanisms to accelerate the release of GHGs such as methane, (4) uncertainty of the effects (that is, damages) of extreme climate change,¹⁹ and (5) the proper discounting of the distant future (Weitzman 2011). At each of these steps in the climate model, parameters are highly uncertain and potentially represented by fat tails. As a consequence of the "cascading" uncertainties at each step in the climate model and the potentiality of fat tails at each step, climate impacts are also likely fat tailed. As Weitzman (2011) emphasizes, this is the fat tail that truly matters to climate economics—not the fat tails of the climate sensitivity parameter and the other parameters—for the Dismal Theorem to arise.

As a result of the potential for climate impacts having a fat tail, Weitzman develops a theory now dubbed the Dismal Theorem. According to Weitzman (2009), if IAMs were to model fat-tailed distributions, the expected marginal utility of consumption would "explode." In other words, the "limiting [willingness to pay] to avoid fat-tailed disasters constitutes all of output (Weitzman, 2011)." As a consequence of this result, traditional BCA collapses as the SCC becomes infinite.

While Weitzman (2009) suggests such events can have such large costs as to overwhelm the discount rate,

Nordhaus (2009) finds Weitzman's results are exceptions to the rule. In particular, Nordhaus (2009) find that the Dismal Theory holds, that is, the expected cost of climate change is infinite, only under limited conditions: the tails are “very” fat or society is “very” risk adverse. In other words, “[the probability of a catastrophic event] must not go to zero and [marginal utility of consumption] must be indefinitely large as consumption declines” towards zero (Nordhaus 2012); Nordhaus argues that the former condition may not hold (particularly if there is an upper bound on climate parameters), and the latter condition does not hold. Furthermore, using DICE-2007, Nordhaus (2009) demonstrates that catastrophic outcomes are potentially avoided, even if the climate sensitivity parameter is high and major tipping points exist, if policymakers can learn about the risks of climate change before irreversible, catastrophic damages occur and policymaking works correctly. However, Nordhaus' rebuff of the Dismal Theory (and its implication that BCA does not apply to climate change) should not be construed as a rejection of fat tails—these he believes are important for inclusion in IAMs (Nordhaus 2012).

In response, Weitzman (2011) argues that the infinite number should not become a distraction, but merely emphasize the larger willingness to pay to avoid these structural uncertainties discussed above. To produce a finite SCC for BCA to continue, Weitzman argues for the inclusion of the value of civilization. Like the value of a statistical life, the value of civilization captures the “rate of substitution between consumption and the mortality risk of a catastrophic extinction of civilization or the natural world as we know these concepts (Weitzman 2009).” Crudely calculated, the value of civilization equals the present value of global income in the year that civilization would end divided by the probability that civilization would end in that year (Weitzman 2009; Weitzman 2011).²⁰

The empirical work on catastrophic damages, that is, the willingness to pay to avoid structural uncertainty, finds mixed results. On the one hand, Newbold and Daigneault (2009) find large catastrophe risk premiums. In this case, the use of the value of civilization may be essential. On the other hand, Pindyck (2009) finds only a modest risk premium. Similarly, Nordhaus (2009) only finds large catastrophic damages when climate policy fails in the presence of high climate sensitivity and major tipping points. In these cases, the inclusion of a value of civilization may be unnecessary because benefit-cost analysis does not collapse.

Note that there is some overlap between tipping point events and fat tails. If tipping point damages are modeled explicitly, the probability of incurring tipping point damages can be modeled using a fat-tailed distribution if the probability distribution function of the event occurring is unknown. Similarly, the corresponding magnitude of the damages can be modeled using fat-tailed distributions if this probability distribution function (PDF) is also uncertain. If tipping point damages are modeled implicitly, that is, climate parameters are used to model tipping points explicitly, fat-tailed distributions can be used for the corresponding climate parameters' probability distribution functions. However, tipping points do not require fat-tail distributions if they are known unknowns. In other words, the use of fat tails to model the probability of tipping points or their damages is not necessary to the extent that their probability distribution functions are known, and they can be captured by thin- or medium-tailed distributions. Undoubtedly, some tipping points are unknown unknowns and require the use of fat tails in that probability and damages of tipping point scenarios are poorly understood (Weitzman 2011).

BLACK SWAN EVENTS. Black swan events refer to unknown catastrophic impacts, via unknown tipping point events or parameters within unknown probability distribution functions. Currently, black swan events still go unaddressed by IAMs. Along with the view that omitted climate damages likely outweigh omitted climate benefits (Mastrandrea 2009), there exists a general opinion that bad surprises are likely to outweigh good surprises in the case of climate change (Tol 2009b; Mastrandrea 2009).²¹

Just as tipping points and fat tails are related concepts, so are fat tails and black swan events. Fat tails can be thought of as a general way to capture unknown unknowns in the SCC. However, the choice of fat-tailed distributions, that is, the rate that the tail declines, is unknown. In other words, specifying a fat-tailed distribution is guessing at unknown unknowns. Furthermore, in terms of real practical applications, IAMs that include fat tails may still omit other unknown unknowns. In this sense, the inclusion of fat-tailed distributions into IAM models may not fully capture unknown unknowns.

CALIBRATION

Through the choice of damage sectors and the choice of calibration estimates, IAM developers determine what damages from climate change are included and excluded in the social cost of carbon.²² Using damage estimates (measured as a percentage change in GDP) for a specified temperature increase (measured as the degree Celsius increase in regional or global average temperature from the pre-industrial temperature) drawn from the literature,²³ IAM developers calibrate damage functions in three ways: sector-region analysis, survey, or meta-analysis.

First, a sector-regional analysis is when studies are found that provide sector-specific damage estimates by region; extrapolation from observed regional damages to missing regions is often necessary. If an aggregate damage function is utilized, damages are summed across sectors and regions. Earlier versions of DICE (DICE-1999 and DICE-2007) fall within this category, as does FUND.²⁴ Second, a survey of the literature is when a consensus work, like the IPCC studies, is utilized, or when the author uses his discretion to decide on the level of damages. In either case, though no statistical analysis is performed, the damage estimates are based upon a survey of particular studies. PAGE relies on this methodology combined with uncertainty analysis.²⁵ Third, a meta-analysis is when a damage curve is fit to various damage estimates that vary in damage magnitude and future temperature level. The most recent version of DICE relies on this method. The latter two methods are problematic in that they make it difficult to determine the actual source behind the damage function, and thus, to determine what particular climate damages are included and excluded from the model.

In the following section, we discuss how each IAM is calibrated by its developer using the default version of each of these models.²⁶ This is done to reflect the version of the model that each modeler provides to the public and documents most thoroughly. Furthermore, the IWG uses the default versions of these IAMs. In the case of DICE-2013, which has not been utilized by the IWG, the default version is utilized for purposes of consistency.

Calibration of the DICE damage function

Since 2000, William Nordhaus has released four versions of the DICE model: DICE-99, DICE-2007, DICE-2010, and DICE-2013. Of these four models, DICE-2010 is not considered a major update of the DICE model but rather an aggregation of the RICE-2010 model, a regionalized version of DICE. Across all versions of DICE, William Nordhaus calibrates an aggregated global damage function that is quadratic in temperature.²⁷ The sources used to calibrate the DICE-RICE damage functions have changed over the various versions of the model. For the quadratic damage functions of the initial models, that is, DICE-99, DICE-2007, and DICE-2010, Nordhaus used damage estimates by sector drawn from specific sources and studies. For the more recent version of the model, that is, DICE-2013, Nordhaus utilizes a meta-analysis approach.

EARLY VERSIONS OF DICE. The DICE-99 damage function was calibrated against region-sector damage estimates for a 2.5 degree and 6 degree Celsius increase in global mean surface temperature above the pre-industrial level.²⁸ The sectors in the DICE-1999 model are: agriculture; other vulnerable markets—forestry, fisheries, water transportation, hotels and other lodging places, outdoor recreation, and energy; coastal—sea level rise and storms; health—malaria, dengue fever, other tropical diseases, and pollution; non-market amenities—the allocation of time to leisure activities; settlements and ecosystems; and catastrophic impacts. Thus, the DICE-1999 model includes market, non-market, and catastrophic damages. See Table 4 for sources of damage estimates and Table 5 for DICE-1999 region-sector specific damage estimates.²⁹ See forthcoming Appendix A for a full discussion of the calibration of DICE-1999.

Instead of DICE-1999, the 2010 Interagency Working Group utilized DICE-2007 in the estimation of the U.S. Social Cost of Carbon, as documented in the 2010 Technical Support Document. There are no major changes from DICE-1999 to DICE-2007. In particular, as with DICE-1999, Nordhaus uses sector-based damage estimates to calibrate the aggregate DICE-2007 damage function. There is no change in the types of damages.³⁰ See forthcoming Appendix B.

The 2013 Interagency Working Group utilized DICE-2010 to estimate the U.S. Social Cost of Carbon, as documented in the 2013 Technical Support Document. The actual calibration method is almost identical to DICE-2007. The main difference is that for the 2010 version of the model, Nordhaus explicitly specifies the aggregate damage function as a quadratic function of both sea-level rise and temperature, instead of only temperature (Nordhaus, 2010; Nordhaus and Sztorc, 2013). See forthcoming Appendix C.

Given the similarities between DICE-1999, DICE-2007, and DICE-2010, this paper focuses on the omitted damages from DICE-1999. Of these three versions of DICE, DICE-1999 is chosen because it is used by Hope as one of the calibration sources of the PAGE09 damage function.

RECENT VERSION OF DICE. Nordhaus states that DICE-2013 is the first major update of the DICE model since the 2007 version. There are three major updates from 2007 to 2013 in the DICE aggregate damage function. First, Nordhaus updates the sources of his damage estimates used for calibration. Instead of using Nordhaus and Boyer (2000) as the basis of this calibration, he uses the damage estimates in Table 1 of Tol (2009), as seen in Table 7 below and Figure 2 in Nordhaus and Sztorc (2013). Second, he increases these damage estimates by 25 percent to account for omitted non-monetized benefits, such as “several important factors (biodiversity, ocean acidification, and political reactions), extreme events (sea-level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages).” Last, Nordhaus no longer utilizes a sector-region analysis to calibrate DICE’s aggregate damage function, but instead switches to the meta-analysis technique; see forthcoming Appendix D.

Determining what damages are included and excluded from the DICE-2013 damage function is difficult. This is because Nordhaus switches from a sector-region analysis to calibrate DICE’s aggregate damage function to the meta-analysis technique, which relies on 13 studies cited in Tol (2009); see Table 7. For several reasons, this makes determining the damages included in the DICE-2013 model nearly impossible. First, many of the studies cited in Tol (2009) rely on a multitude of studies to produce their estimates, resulting in the need to go through a large number of papers in detail to decipher what damages are included and excluded from DICE. Second, when these studies do not rely on a multitude of cited papers, they utilize author discretion or statistical techniques to determine damage estimates. Both of these methods make it difficult to determine which sectors are included

in the damage estimates, and the latter estimates, which include cross-national regressions, can often suffer from statistical inference problems. Last, it is difficult to determine what damages are included in the damage function because the 13 studies differ in what damages they include and exclude in their analyses. Specifically, what does it mean to have one of 13 studies include catastrophic damages or three out of 13 studies explicitly model the effect of climate change on vector-borne diseases? It seems reasonable to argue that the inclusion of these damages by a minority of studies implies their general exclusion from the DICE-2013 damage function. However, two studies exclude non-market damages and another two studies exclude market damages. Are non-market damages and market damages completely accounted for in DICE-2013? The answer to this question is debatable.

The DICE-2013 damage function was not used by either the 2010 or 2013 Interagency Working Group because the model was not yet peer-reviewed. It is our view that the IWG should be wary of using DICE-2013 in the future, given the inherent difficulty in understanding its foundations. Furthermore, if a meta-analysis is used, it should be conducted at either the sector or region-sector levels where more data are available. This is discussed further in the conclusion.

Calibration of the FUND 3.6 damage functions

FUND 3.6 is the only model of the three to model damages as functions of physical processes. Specifically, in FUND, Tol calibrates sector-specific damages functions to a 1 degree Celsius increase in temperature, and assumes dynamic equations to extrapolate damage estimates to higher temperature levels and different future states (rate of climate change, CO₂ levels, and socio-economic scenarios). These equations depend on various assumptions about physical and economic processes, and also rely on additional parameter calibration. Unlike DICE and PAGE, some sector damages, that is, agriculture and ecosystem services, are functions of the rate of temperature change, in addition to the level of temperature change, sea-level rise, and amount of CO₂ in the atmosphere.

FUND includes market and non-market damages, but fails to explicitly model catastrophic damages. The model's damage sectors include: agriculture, energy consumption, forestry, (fresh) water resources, sea level rise, human health, ecosystem degradation, and extreme weather (Anthoff and Tol, 2012). While FUND does not explicitly model catastrophic damages, FUND captures catastrophic damages via uncertain parameters.³¹ Of the three IAMs utilized by the IWG, FUND 3.6 is the only one to model a socially contingent response to climate change: migration from sea level rise.

For FUND 3.6, Anthoff and Tol (2012) calibrate multiple damage functions per sector. Tol and Anthoff (2013) calibrate three agricultural damage functions using agricultural damage estimates derived using a general equilibrium approach; the three damage functions model the effect of rate of climate change (the cost of farmer mal-adaptation), level of climate change (effect of temperature level on crop production), and carbon dioxide fertilization on agricultural production (potential increases in agricultural production due to a rise in the atmospheric concentration of CO₂), respectively. In energy, Anthoff and Tol include the cost to the energy sector due to increased demand for space cooling and decreased demand for space heating from a rise in temperature. In forestry, Anthoff and Tol (2012) include the cost of climate change impacts on industrial wood manufactured products from changes in mean temperature and atmospheric concentrations of carbon dioxide relative to pre-industrial levels. In water resources, Anthoff and Tol (2012) include the effect of climate change on fresh water resource. For sea level rise, Tol accounts for losses of dry land and wetland, the coastal protection

and migration costs. In health, Tol accounts for the mortality and morbidity costs of diarrhea, vector-borne diseases (malaria, schistosomiasis, and dengue fever), and heat and cold related illnesses (cardiovascular and respiratory disorders) due to a rise in temperature. With respect to ecosystems, Anthoff and Tol (2012) estimate a value for species loss. Finally, with respect to storms, Tol estimates the economic costs of the destruction and the value of life lost from tropical storms (hurricanes, typhoons) and extratropical storms (cyclones).

Due to the extensive use of data sources necessary to calibrate the physical processes, this section does not contain an extensive discussion of data; see forthcoming Appendix E.

Calibration in the PAGE-2009 damage functions³²

PAGE09 models damage functions for four generalized impact sectors: market, sea-level rise, non-market, and non-linear (or tipping point) damages. Hope (2011a; 2011b; 2013) specifies a triangular distribution for each of the parameters in the damage function.

The non-catastrophic damage functions in PAGE09 (market, non-market, and sea-level rise) are calibrated using various versions of DICE and FUND. Thus, PAGE09 omits similar damages as do these two models. In PAGE09, Hope calibrates the distribution of economic (that is, market), non-economic (that is, non-market), and sea-level rise damages as a percentage of GDP for a 3 degree temperature increase (corresponding to a 0.5 meter sea-level rise) using a range of damage estimates from Warren et al (2006) and the IPCC 4th Assessment Report (IPCC, 2007). Warren et al (2006) discusses DICE-1999, FUND2.9, PAGE02, and MERGE; PAGE2002 is calibrated based on DICE-1999 and FUND 2.0.³³ Fig 20.3a from AR4 WGII on page 822 (Figure 1 below), which is used to inform the range (the minimum and maximum combined effect) of market and non-market damages (a range between 0.3 percent to 1.8 percent GDP decline for a 2.5 degree Celsius increase), cites Nordhaus and Boyer (2000) – DICE-1999, Tol (2002b) – FUND 2.0, and Mendelsohn et al (2000); this figure is identical to Figure 19.4 in IPCC (2001a, Chapter 19) upon which the PAGE2002 damage estimates were partially based. In other words, the market, non-market, and sea-level damage functions in the PAGE09 model are “highly” dependent on DICE and FUND, though Hope uses his discretion to specify a range of estimates to allow for the possibility that these models have underestimated impacts.



Flooding in downtown Binghamton, New York due to the remnants of Tropical Storm Lee. Photo: National Weather Service, Binghamton

Hope (2011) also reduces the magnitude of these damages by including initial climate benefits, which can result in some regions experiencing positive net benefits from climate change at low temperature increases, and by placing a limit on climate damages so that they can be no greater than 100 percent of GDP at high temperature increases. In addition to damages, Hope (2011b) includes an additional terms in each of the three non-catastrophic impact sectors based on the findings of Tol (2002) to capture initial climate benefits for lower temperature increases; these initial benefits are set equal to zero for sea-level rise in the default version of the PAGE09 model.³⁴ These expressions are defined such that these benefits dissipate as temperature increase until they become zero (that is, do not yield any actual benefits) at some temperature threshold, and then they become damages (in addition to the previously discussed calibrated damages) for further temperature increases. Assuming no adaptation, the temperature thresholds for both market and non-market damages are 3 degrees Celsius.³⁵ Hope (2011) also limits damages to 100 percent of GDP in any given time period. Instead of maintaining polynomial damage functions across all temperature levels, damage functions shift from polynomial functions to logistic functions at certain damage levels to constrain damage to 100 percent of GDP. Following Weitzman (2009), the saturation point (that is, the point where damages as a percentage of consumption starts to become limited) is characterized by a triangular distribution with range 20 percent to 50 percent, a mean of 33.33 percent, and a mode of 30 percent (Hope, 2011a; 2011b). Given the modeling assumption of PAGE09, the initial benefit terms do not yield any actual benefits (that is, are equal to zero) and the damage functions are still polynomial functions for a 3 degree Celsius increase and a 0.5 meter sea-level rise. In other words, non-catastrophic damages equal their calibration value of 2.03 percent of GDP at the calibration temperatures increase of 3 degrees Celsius when there is no adaptation (Hope 2011).

In PAGE09, Hope explicitly models climate tipping points as a singular, discrete event that has a probability of occurring in each time period. This probability increases in temperature. If this event occurs, a decline of 5 percent to 25 percent of GDP occurs; See Table 9 below.³⁶

PAGE09 calculates climate damages for the European Union, and then scales these damages to other regions. PAGE09 uses the relative length of coastline to inform the corresponding ranges of scaling factors; Anthoff et al., (2006) is the data source for the weighting factors. While these scaling factors do not differentiate between developed and developing countries, Hope includes equity weights in PAGE09 that account for differences in GDP per capita between European Union and other regions (Hope 2011b). Finally, Hope specifies regional damage functions in PAGE09, which are functions of regional temperature, not global mean surface temperature. Thus, PAGE09 captures some regional differences in climate damages using several mechanisms. See forthcoming Appendix F for further discussion.

Damages generally included in IAMs

From this discussion about how the three latest IAMs are calibrated, we can make some general statements about what types of damages are accounted for by IAMs. Currently, they cover a number of direct effects of climate change, that is, a rise in global average surface temperature, on economic (that is, market) activity, and to a lesser extent the direct effects of climate change on the environment and human settlements. The three Integrated Assessment Models (IAMs) capture the direct effects of higher temperature levels and higher CO₂ levels (via soil fertility) on agriculture and forestry yields (but excluding climate change effects on pests, pathogens, and fires), and the effects of trade through general equilibrium effects. The models only capture the effects of higher temperature on fisheries to a very limited extent, and exclude the effects of habitat loss (particularly mangroves and coral reefs), ocean acidification, and invasive species all together. The models

also capture some effects of climate change on energy demand and fresh water resources, though these are still limited in important ways (see discussions on fisheries, energy supply, ecosystem services, and destabilizers of existing non-climate stressors below). While IAMs capture the effects of heat and cold related illnesses (cardiovascular and respiratory disorders) to different extents, all three capture some effects of climate on vector-borne diseases, including malaria and dengue fever. For example, the direct cost of vector-borne diseases on human life is included, but not the effects of such diseases on labor supply or productivity (as discussed below). To different extents, all three models capture the effects of increased storm strength on coastal property values and sea level rise on preventative expenditures, lost property, and lost ecosystems. To the extent possible with current models, all IAMs consider some effect of climate change on ecosystems and biodiversity—though improved estimates are needed with respect to both of these damage estimates. Finally, there are a variety of damages that are captured by only one or two of the IAMs, but not all three: effects of climate change on morbidity; mortality from storms, pollution, and diarrhea; recreational activities; climate amenities (that is, the willingness to pay to live in a location with more sunny days); and catastrophic damages.

As is discussed more thoroughly in the conclusion of this report, many of the smaller climate damages are not considered by the authors of IAMs because they are considered cancelled out by omitted climate benefits. The views of Tol (2009) and Yohe and Tirpak (2007) are that a better job has to be done with respect to including only major damage categories: catastrophic damages, socially contingent damages, and weather variability. See the conclusion of this paper for more of a discussion.

CAUSES OF THE OMISSION OF DAMAGES

In general, the more difficult a climate impact is to estimate in the natural sciences (which measure the physical impact) and/or value in economics, the more likely that climate impact is to be excluded from IAMs (Yohe and Tirpak, 2008); see Figure 2. With respect to the natural sciences, damages corresponding to more certain (that is, known) climate trends (for example, average temperature increases and sea level rise) are included in IAMs; bounded trends, that is, climate change for which a range and/or distribution is specified, such as extreme weather events and weather variability (for example, droughts, floods, storms, and so on), are less likely to be included; and abrupt changes, in general, are the least likely to be included because they are the effects characterized by the greatest uncertainty. With respect to economics, damages that are easier to value are more likely to be included, such that many more market damages are included than non-market damages. Environmental goods and services are more likely to be omitted from IAMs by analysts than market damages because the former does not have observable market prices and instead must be valued by the analysts. While the value of some environmental goods and services can be indirectly observed in market data (for example, housing sales) using revealed preference techniques, other environmental goods and services (for example, biodiversity) can only be valued using stated preference techniques;³⁷ this latter group of environmental goods and services are more likely to be omitted. Socially contingent damages (for example, famine, political unrest, migration, and so on), which are often the result of multiple stressors, are usually omitted because they are difficult to quantify, predict, and value (Yohe and Tirpak, 2008). Figure 2 below, taken from Yohe and Tirpak (2008), organizes all types of climate damages into nine categories of damages corresponding to three levels of scientific uncertainty (that is, three rows) and three levels of economics uncertainty (that is, three columns) discussed above.

The nine categories of climate of climate benefits and damages in Figure 2 (and discussed in the previous

paragraph) can be further organized into three groups of damages based on their levels of representation in IAMs:

- Group 1: Included damages—market damages from certain climate trends. Area I in Figure 2.
- Group 2: Partially included damages—bounded and tipping-point market damages and certain and bounded non-market damages. Areas II, III, IV, and V in Figure 2.
- Group 3: Excluded damages—socially-contingent damages and non-market tipping point damages. Areas VI, VII, VIII, and IX in Figure 2.

Group 1 damages, that is, certain market damages, are included, but can still be improved by accounting for geographic variability. Other market damages, for all real purposes, are excluded: fisheries, energy supply, transportation, communication, and recreation and tourism.

Group 2, which includes bounded and tipping-point market damages and certain and bounded non-market damages, has been less successfully included into IAMs. The three IAMs have included certain and bounded non-market damages, but in a less than comprehensive manner due to data and method limitations. In other words, while many of these damages have been included in IAMs (for example, heat stress, loss of wetlands, biodiversity, and loss of life), the included estimates require significant improvement.³⁸ Similarly, while some IAMs (earlier versions of DICE and PAGE), have explicitly accounted for catastrophic market damages, Yohe and Tirpak (2008) argue that these estimates have been less than comprehensive, and most likely omit non-market and socially contingent consequences of these changes.³⁹ Furthermore, while IAMs have included market sectors that are affected by climate variability (agriculture, fresh water resources, forestry), little has been done to account for the damages of increased climate variability in these sectors. It is critical to account for increased climate variability because average changes mask extreme events, such as droughts, heavy rains, heat waves, and cold spells.

Group 3, that is, socially contingent damages and non-market tipping point damages, has only recently been investigated (or has not been investigated at all) by impact papers. As a consequence, they are completely omitted from IAMs (Yohe and Tirpak, 2008).

With each generation of IAM, a discussion ensues over whether climate damages are accurately captured. While several studies have identified missing damages in earlier versions of these three IAMs (Warren et al., 2006; Dietz et al., 2007; Yohe and Tirpak, 2008; Tol, 2009), this report is the first to thoroughly identify and discuss the various damages omitted from the most recent versions of these three IAMs (specially the default versions): DICE-2013, FUND 3.6 (which is identical to FUND 3.7 and FUND 3.8 in terms of damage captured), and PAGE09. By analyzing the calibration methods and data sources of the latest version of the three IAMs, as discussed in the previous section, this report is able to provide a comprehensive discussion of which important categories of harm are included and excluded from these IAMs. Please see Appendices A through F for a more thorough discussion of the calibration of each IAM, and which damages are included and excluded from the default version of each of these models.

OMITTED DAMAGES

Based on the analysis of the three IAMs in the previous two sections, this section will discuss the damages currently omitted from IAMs: market damages—fisheries, pests (IWG, 2010), pathogens (IWG 2010), erosion (Vose et al., 2012), weeds (Rosenzweig et al., 2001), air pollution (Warren et al., 2006; Cline, 1992), fire (Cline, 1992), energy supply (Tol, 2009; IPCC, 2007b), transportation (IPCC, 2007b; Koetse and Rietveld, 2009), communication, ecological dynamics (Gitay et al., 2001; Norby et al., 2005), and decreasing growth rate (Fankhauser and Tol, 2005; Tol, 2009; Dell, Jones, and Olken, 2013; Moyer et al., 2013); non-market damages—recreational value (Tol, 2009), ecosystem services, biodiversity and habitat (IWG 2010; Tol, 2009; Nordhaus and Sztorc, 2013; Freeman and Guzman, 2009), omitted health costs (Tol, 2002a; Warren et al., 2006), and relative prices (IWG, 2010; Sterner and Persson, 2008; Hoel and Sterner, 2007); socially contingent damages—migration, social and political conflict, and violence (Stern, 2007—Chapter 6; Yohe and Tirpak, 2008; Tol, 2009; Dell, Jones, and Olken, 2013); catastrophic impacts (IWG 2010; Yohe and Tirpak, 2008; Tol, 2009); inter-regional damages (IWG 2010); and across sector damages—inter-sector damages (IWG, 2010; Warren et al., 2006), exacerbation of existing non-climate stresses (Freeman and Guzman, 2009), ocean acidification (Brander et al., 2009; Cooley and Doney, 2009; Guinotte and Fabry, 2009), and weather variability (Yohe and Tirpak, 2008; IWG, 2010).⁴⁰

Omitted damages can involve omitted damage sectors, such as fisheries, or omitted effects of climate change within and across sectors, such as ocean acidification. This poses a taxonomy problem in that it is hard to classify damages within the simple market, non-market, socially contingent, and catastrophic damage categories that we have laid out earlier. For clarification purposes, we highlight when this is a particular problem with respect to omitted effects of climate change: ocean acidification; wildfires; and pests, pathogens, and weeds.⁴¹ In addition, we add two additional types of omitted damages to the taxonomy: inter-sector damages and cross-sector damages. The former captures the damages that arise due to the interaction of climate change effects between two or more damage sectors, and the latter captures omitted damages that affect multiple sectors. See Table 10 for the taxonomy of omitted damages used in this paper, and Table 11 for an alternative taxonomy based on omitted damage sectors and omitted climate effects.

Market damages

There exist several market damages that remain unaccounted for in the market damage literature. As mentioned earlier, Yohe and Hope (2013) argue that few updates to market damages will have a significant effect. However, there are several potential additions that should be considered for having potentially large effects: fisheries (and relatedly, including effects of ocean acidification more broadly), market sector disturbances (pests, pathogens, air pollution, erosion, and fires), energy supply, transportation, and economic growth.

FISHERIES. Fisheries are, for the most part, excluded from IAMs. DICE-1999, which is utilized as a damage source in DICE-2010 and PAGE09 (both are used by the 2013 IWG), includes fisheries in a generalized “other market” sector, along with forestry, energy systems, water systems, construction, and outdoor recreation. Citing Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999) damages estimates to these sectors for the United States, Nordhaus and Boyer (2000) argue that damages not related to energy are equal to zero. Implicitly, this assumes that climate damages to fisheries are equal to zero even though the sources he cites do not explicitly discuss damages to fisheries, particularly Cline (1992) and Nordhaus (1991). As a consequence, Nordhaus and Boyer (2000) essentially fail to account for fisheries. In FUND 3.6, freshwater and saltwater fisheries are excluded. Consequently, PAGE09, which heavily relies on early versions of DICE and FUND to calibrate its

market damage function, excludes fisheries as well. Finally, DICE-2013, at most, partially captures fisheries. Many of the enumerative studies upon which DICE-2013 relies in the calibration of its damage function, exclude fisheries altogether.⁴² Similarly, in the statistical studies, the effect on fisheries, particularly offshore salt-water fisheries, may be excluded; see forthcoming Appendix D.⁴³

Fisheries support a significant portion of the world's population. Many individuals rely on fishing and aquaculture for employment. Also, many individuals rely on seafood as their primary source of protein. Climate damages to fishery resources will cause particular harm to those regions most reliant on fisheries (WFC, 2007). According to Allison et al., (2009), the most vulnerable fisheries are located in developing nations, which are the most dependent on fisheries in terms of livelihood and nutrition.

Climate change will affect fisheries in several ways. First, rising sea surface temperatures will damage coral reefs, an important habitat for many fisheries, and result in more frequent algae blooms, which negatively affect fish stocks via decreased oxygen availability. Rising temperatures will also positively affect the growing season, winter mortality rates, and growth rates. Second, rising land temperatures will increase the temperatures of fresh water systems, resulting in declined fish stocks through reduced water quality, invasive species and pathogens, and decreased food abundance; again, warmer temperatures in cold waters may have some benefits in terms of increased growth rates. Third, rising sea levels will negatively affect coastal habitats, including mangroves and salt water marshes, and freshwater water habitats via saltwater intrusion; rising sea levels may also benefit shrimp and crab aquaculture. Fourth, increased weather variability and extreme events, including floods and droughts, and decreased water availability in some regions is likely to negatively affect fish stocks, particular fresh water and aquaculture; changing precipitation patterns may affect marine populations via water salinity (WFC 2007). Fifth, changes in ocean chemistry, including ocean acidification, which is discussed more below, and decreased oxygen content from increased algae blooms, which is discussed above, will negatively affect fish stocks, particularly mollusks. Sixth, melting sea ice may increase access to Arctic fisheries. Last, climate change will likely compound the negative effect that human activity, including over fishing, has on future fish stocks.⁴⁴ These damages and benefits will vary regionally, particularly as fish shift locations. They are also highly uncertain due to uncertainty over climate change and its effects (particularly on the scale that is relevant to marine life and fisheries – continental shelves), complex aquatic food web and ecosystem dynamics, the ability of species to adapt, and the range of human and environmental impacts fisheries (WFC, 2007; Hollowed et al., 2013; Sumaila et al., 2011).

Adaptation by species and humans may be able to reduce these negative effects. Fish species will be able to adapt to some of these change by moving toward the Poles and into deeper water (Sumaila et al., 2011). However, these changes may still result in habitat loss for some freshwater and saltwater fish, even with this ability to adapt, such that some species will experience declines and extinction (Hollowed et al., 2013). Furthermore, these shifts imply regional effects, such that some regions benefit and others are harmed (Hollowed et al., 2013), and quality effects, as fisherman are forced to switch to new species. Finally, humans may be able to adapt to mitigate losses and meet increased demand by expanding aquaculture to replace decreased wild catch and increasing trade (Brander 2010). However, human adaptation at the local level will come at an increased capital cost, and a loss of capital as some fisherman scrap their vessels (Sumaila et al., 2011).

In addition to climate change affecting fish stocks, climate change will also affect human capital and infrastructure necessary for production. Increased storm strength and frequency will negatively affect infrastructure, particularly aquaculture, located near coastal areas. Coupled with rising sea levels that will negatively affect coastal ecosystems that act as a buffer from coastal storms, storm effects could be significant (WFC, 2007). The

ability of regions to adapt to these events will vary regionally.

There is a lack of estimates for the impacts of climate change on fisheries (Sumaila et al., 2011). This is partially due to the difficulty of estimating the net impacts on production across multiple species and uncertain future environments, which results in highly uncertain estimates. While it is clear that damages will vary regionally—hurting tropical regions and possibly benefiting arctic regions—these regional results are uncertain given the large scale effects of climate change on oceans; this includes ocean acidification and higher ocean temperatures—both of which effect phytoplankton (Toseland et al., 2013).⁴⁵ Because developing nations are focused predominately in tropical and subtropical subclimates, fishing industries in poor nations are likely to be disproportionately affected. These nations are often already at an open-access equilibria due to overfishing and lack of management, and, as a consequence, are unlikely to experience a significant change in profits due to climate change. However, in developing nations, large portions of the population rely on subsistence fishing for calories and protein. Thus, the effects of climate change on consumer welfare via fisheries are likely to be substantial in developing nations.

NATURAL DISTURBANCES: PESTS, PATHOGENS, AND WEEDS, EROSION, AIR POLLUTION, AND FIRES. Pest (weeds and insects) and pathogens (Rosenzweig et al., 2001), erosion (Vose et al., 2012), air pollution (for example, the effects of climate change on increased ozone pollution, which affects crops and public health),^{46,47} and fire are natural disturbances that affect agriculture and forestry. While these disturbances are currently being excluded from the agricultural and forestry sectors (Ackerman and Stanton, 2011, Cline 1992), these disturbances are likely to be substantially affected by climate change (IPCC, 2007b, Chapter 5). Climate may expand the geographical extent of pests, pathogens, and weeds (particularly for livestock and forests) and increase the likelihood and severity of pest and pathogen outbreaks due to earlier springs and more extreme events. Forestry may be negatively affected by increased erosion from higher precipitation and other extreme weather events (Vose et al., 2012). Increased ozone exposure will also decrease timber production and crop yields, while increasing crop susceptibility to pest outbreaks. Increased fire risks may decrease forestry production and costs (IPCC, 2007b), and have significant impacts on human health and infrastructure (Fowler, 2003). While each of these natural disturbances may have only modest effects, their interactions (along with drought) and their combined effects are likely to be substantial.

These natural disturbances also affect agricultural and forestry via the fertilization effect, which is the increase in plant growth, and thus production, from an increase of carbon dioxide in the atmosphere. Current estimates of the CO₂ fertilization effect are from laboratory experiments where plants are not subject to competition from pests, pathogens, and weeds that may also benefit from CO₂ fertilization.⁴⁸ More recent estimates, known as Free-Air CO₂ Enrichment (FACE) experiments, are field experiments where plants are subject to these pressures; the resulting benefits from increased CO₂ are lower under FACE experiments (Hanemann, 2008, IPCC, 2007a). Furthermore, air pollution (ozone), which is completely unaccounted for, may further limit the CO₂ fertilization effect (IPCC, 2007b Chapter 5).

Increased pests, pathogens, and weeds, erosion, air pollution, and fires will also affect ecosystems, wildlife, and human settlements. These costs are also currently excluded from the default versions of these IAMs.

ECOLOGICAL DYNAMICS. Ecological dynamics are omitted from the analysis despite their significance in timber production. In addition to disease and insects (Gitay et al., 2001; Norby et al., 2005) and wildfires, studies of climate change impacts on ecological dynamics of forests cited by Gitay et al., (2001) include those concerning, seasonality, timing of freeze-thaw patterns, length of growing season, nutrient feedbacks, disturbance, diurnal temperature patterns, local climatic extremes, late and early frost, changes in precipitation, and extreme

weather events. Climate change will further affect forestry to the extent that these dynamics contribute to forest ecology and will be impacted by climate change.

ENERGY SUPPLY. Tol (2009) argues that energy costs may decrease due to climate change relative to a future world without climate change. This is due to decreased costs of supplying renewable energy from wind and wave sources, and the increased availability of oil due to higher temperatures in the Arctic. However, warmer water temperatures will increase the cooling costs of thermal power plants (conventional and nuclear), and decreased water availability in some regions may increase the cost of hydro-electric energy (IPCC, 2007b Chapter 1 and Chapter 7). The increased frequency and intensity of extreme weather events (heat waves, droughts, and storms) have the potential to further disrupt energy supplies, particularly coastal energy and energy transmission infrastructures, while the melting of permafrost is also threatening energy infrastructure in Arctic regions (IPCC, 2007 Chapter 7). It is difficult to determine whether the net effects of climate change on the cost of supply energy will be positive or negative.

TRANSPORTATION. Transportation is critical for the movement of populations and goods, including energy resources. However, the effects of climate change on the transportation sector in terms of lost infrastructure, costs, delays, and safety (including fatalities) are rarely emphasized according to Koetse and Rietveld (2009). This may partially be due to the sparse literature in this area and the general ambiguous effects of climate change on transportation due to countervailing effects (Koetse and Rietveld, 2009).

On the one hand, higher temperatures imply fewer transportation delays from snow and ice (Tol 2009, IPCC 2007). While traffic congestion and accidents result from adverse weather conditions (including rain, snow, and poor visibility), less snow overall will result in less traffic congestion and fewer accidents. Furthermore, many areas will experience decreased costs of dealing with these cold weather events, including less salting of roads and plowing equipment. While higher temperatures will also come with some costs, including buckled rails and roads, these costs can likely be overcome gradually with updating of the road and railway systems during their regular maintenance schedule. Higher temperatures also decrease ice cover in rivers, lakes, and oceans, which decreases shipping costs during the winter. In particular, higher Arctic temperatures may make shipping through the Northwest Passage possible at some times during the year; this has the potential to lower overall shipping costs (Koetse and Rietveld, 2009; IPCC, 2007).⁴⁹



The BLM and the U.S. Forest Service work together to manage wildfires. Photo: Bureau of Land Management

On the other hand, greater weather variability and a higher frequency of extreme weather events (droughts, heavy precipitation events, floods, high winds, and storms) will potentially hurt traffic and disrupt transportation. While higher temperatures and less snow decrease some effects of climate change on traffic congestion, delays, and accidents, the overall effects are unclear because increased precipitation variability due to climate change will likely have a countervailing effect, as precipitation following a dry spell significantly increases the number of accidents (Koetse and Rietveld, 2009). Similarly, while decreased ice cover due to higher temperatures reduces shipping costs, extreme weather events significantly disrupt transportation and destroy transportation infrastructure. Flooding is particularly problematic for the transportation systems of coastal communities (and potentially the most costly of the transportation effects), while droughts will be more of a concern for inland waterway transportation.⁵⁰ In addition to the inconvenience to travelers, these events could disrupt trade due to the temporarily shutting down of trade routes, road and port closings, and train and airport delays and cancellations. While ports are more affected (in terms of area and numbers effected) by flooding and storm surges than roads, railways, and airports, even small effects to these latter three infrastructures may have significant costs due to network effects.⁵¹ Due to the increase in exposure to extreme weather events, particularly along the coasts, without adaption, the costs from transportation delays and infrastructure losses will undoubtedly be substantial. Furthermore, changing weather patterns may change trade patterns, which may require infrastructure investment, and require that Arctic regions update their transportation infrastructure in response to melting permafrost (Koetse and Rietveld, 2009; IPCC, 2007).

Traffic safety in terms of the frequency of accidents and changes in mortality and injury rates due to accidents is also another important component of transportation costs. While adverse weather increases the likelihood of aircraft accidents, the bulk of deaths related to travel are road traffic related. However, calculating the change in related deaths due to climate change turns out to be complicated because of the complex number of effects: (1) higher temperatures increase the number of accidents due to heat-stress, (2) increased precipitation increases the frequency of accidents, (3) adverse weather decreases the severity of damages due to reduced traffic speed, (4) snowfall causes more accidents than rainfall, and (5) precipitation after a dry spell has a greater effect on accidents and fatal accidents than precipitation alone. Therefore, the effects of climate change on traffic mortalities and injuries are ambiguous, as is the case for traffic safety in general, congestion, and shipping costs. Effects will likely vary regionally (Koetse and Rietveld, 2009).

Adaptation is also likely to reduce some of the costs associated with extreme weather events. In particular, damages due to sea level rise and floods may be preventable through adaptation, including the building of sea walls. As a consequence, many of the current cost estimates available in the literature, which mainly focus on the eastern United States, may be upper bounds.

Current IAMs do not explicitly model climate damages to the transportation sector. DICE-1999 explicitly assumes transportation is negligibly effected by climate change (with the exception of water transportation), though it is possible in early versions of DICE that transportation costs may be captured indirectly through damages to human settlements and sea level rise. Similar to DICE, FUND does not explicitly address transportation costs, though climate damages due to storms and sea level rise may already include some of these costs. Because the market and sea level rise damages in PAGE09 are greatly informed by DICE and FUND, it is unclear the extent to which PAGE09 includes transportation costs. Similar issues arise for DICE-2013.

COMMUNICATION. Communication infrastructure will experience similar disruptions as the energy and transportation infrastructures due to extreme weather. While a possible adaptation is to bury these infrastructures

underground, this strategy is costly (IPCC, 2007). Like energy and transportation, these costs are excluded from IAMs. However, Nordhaus and Boyer (2000) categorize damages to the communication sector as insignificant.

RECREATION. The recreation sector will also be affected by climate change, and is omitted from IAMs according to Tol (2009). While there are clearly redistribution effects across regions, its ultimate effect is uncertain according to Tol (2009). Similarly, Bigano et al (2007) find that climate change has unclear, but generally negligible, effects on global tourist expenditures.⁵² Alternatively, using a general equilibrium model, Berritella et al., (2006) find that “climate change will ultimately lead to a non-negligible global loss” in 2050. This estimate includes only the direct impacts of climate change on recreation, and it omits the indirect impacts such as the loss of some beaches and islands due to sea level rise and the loss of particular ecosystems (such as coral reefs) and species (such as polar bears). The inclusion of these indirect impacts will likely further increase the recreational cost of climate change.

CHANGES IN OUTPUT GROWTH. There is evidence that higher temperatures effect labor productivity (Kjellstrom et al., 2009), the growth rate of economic output (Dell, Jones, and Olken, 2009; Dell, Jones, and Olken, 2012; Hsiang, 2010), and the growth rate of exports (Jones and Olken, 2010), and some of these negative effects on growth continue into the medium-run and long-run (Dell, Jones, and Olken, 2009; Dell, Jones, and Olken, 2012). However, as discussed earlier, the popular IAMs are built on enumerative studies that estimate climate damages to a particular economic (or non-economic) sector of a geographical region in a specific time period. These studies, for the most part, omit dynamic considerations with respect to damages. As a consequence, the current IAMs based upon these estimates fail to model the potential effects of climate change on economic growth—a dynamic phenomenon—and instead focus on the effect of climate change on the level of output (Fankhauser and Tol, 2005, Tol, 2009; Moyer et al., 2013).⁵³

In their default versions, the popular IAMs (DICE, FUND, and PAGE) all assume the relentless march of output growth. In FUND and PAGE, regional GDP per capita growth rates (and total factor productivity growth) are exogenous inputs into the models that are determined by the economic and population scenarios chosen by the modeler. As a consequence, climate change affects consumption only. In DICE, economic growth (increased GDP due to all factors including changes in inputs—labor and capital—and technological progress) is endogenous and total factor productivity growth (increased GDP due solely to technological progress) is exogenous. As a consequence, climate change potentially affects the growth path by decreasing the marginal production of capital (and as a consequence the optimal savings rate) and decreasing output (and as a consequence decreasing the total amount of investment and capital accumulation) for a given savings rate (Fankhauser and Tol, 2005).⁵⁴ However, in DICE, climate change still only has an indirect effect on growth because there are no direct effects of climate change on the inputs of production or total factor productivity. Just as climate change cannot significantly affect the economic trajectory of the global economy in DICE as currently specified, Moyer et al., (2013) shows that climate damage eight to 17-fold higher does not contract economic output by 2300 in DICE. Furthermore, in the U.S. government analysis, the IWG modify DICE to have an exogenous savings rate, such that, like FUND and PAGE, climate change affects only consumption.⁵⁵

The consequence of this unthreatened growth path is that it is not optimal to divert resources for mitigation purposes in the short-run, but rather to continue higher levels of current consumption (and, according to DICE, current investments in capital) (Moyer et al., 2013). In this scenario, the future is always richer than the present due to a growth path of per capita consumption that is rarely overwhelmed by climate change. As a consequence, the discount rate (through the Ramsey equation) almost never declines rapidly, though this prospect is unlikely according to Fankhauser and Tol (2005).^{57,58}

While most IAMs provide estimates of declines in output in the present period and do not analyze the implications of climate change for stable, long-term economic growth, climate change may also affect economic growth of economies (Tol, 2009). In general, the risk of climate change creating long-term implications for economic growth are particularly relevant for less developed countries characterized by low reserves of financial capital (Dell, Jones and Olken, 2008; Aziadaris and Stachurski, 2005). In other words, recent research asks whether the exogenous growth assumption is valid, particularly for developing nations. Dell, Jones, and Olken (2012) find a 1.3 percent decline in the economic growth rate of poor countries for a 1 degree Celsius increase in annual average temperature.⁵⁹ Hsiang (2010) finds an overall decline of 2.4 percent for a 1 degree Celsius increase in Caribbean and Central American countries resulting from declines in the agricultural and non-agricultural sectors. Even small changes in the growth rate, such as 0.6 percent to 2.9 percent declines in the annual growth rate in poor countries would dominate all other economic damage estimates over the three-century timeline of IAMs (as specified in the IWG analysis). In further support of these findings, Jones and Olken (2009) find that a 1 degree Celsius increase in the temperature of a developing nation reduces exports by 2 percent to 5.7 percent.

There are several mechanisms through which climate change can directly affect economic growth. First, poor regions may suffer from further depleted funds due to climate change and be unable to adapt to rising temperatures and other climatic changes. This could result in a poverty trap (Tol 2009). Second, climate change could affect growth rates via a rise in social conflict (Tol 2009). While social conflict may affect economic growth, particularly political violence (Butkiewicz and Yanikkaya 2005), it is unclear by which mechanism this effect may occur.⁶⁰

Third, there is evidence that climate change will directly affect labor productivity through work capacity limits (that is, a physical and/or mental limit on the amount of time or effort that individual can expend in a given day),⁶¹ irritation, and disease (Lecocq and Shalizi, 2007; Tol, 2009).⁶² Dell, Jones, and Olken (2012) summarize much of this literature, including lab experiments and natural experiments, to find that “labor productivity losses ... center around 2 percent per additional 1 degree when baseline temperatures exceed 25 degrees.” These studies generally focus on indoor employment where adaptation is possible, but productivity losses are more substantial for outdoor labor, such as agriculture, and labor intensive industries in non-climate-controlled environments where adaptation to higher temperature and/or avoidance of rain is difficult (Hsiang 2010; Dell, Jones, and Olken 2012). Furthermore, decreased output from climate change could also decrease labor productivity via investments in labor productivity and/or human capital (Fankhauser and Tol, 2005).

In recent work that assumes no adaptation (including increased use of air conditioning), Kjellstrom et al., (2009) estimates labor productivity losses from climate change (resulting from work capacity limits and not an increase in the number of sick days) of up to 11.4 percent to 26.9 percent in some developing regions of the world by 2080. These losses are somewhat reduced when accounting for shifts in regional labor forces between the agriculture sector to industry and service sectors. Using regionalized estimates from Kjellstrom et al., (2009), the authors of ENVISAGE, an alternative IAM, find that declines in labor productivity are of paramount importance in terms of economic damages (accounting for at least three-quarters of all damages). Labor productivity accounts for about 84 percent of total global damage in 2050 and 76 percent in 2100, which is equivalent to a 1.5 percent decline in GDP in 2050 and a 3.5 percent decline in GDP in the year 2100 (Roson and van der Mensbrugghe, 2010).

Fourth, labor supply may potentially fall as labor productivity declines. Most IAMs assume an exogenous labor supply equal to population, such that the labor supply grows according to an exogenous path. However, in labor intensive industries, Zivin and Neidell (2010) find a decrease in the labor supply by as much as one hour

at temperatures above 85 degrees Fahrenheit.⁶³ While there is evidence of partial acclimation and the strong potential for adaptation, accounting for adaptation fully may be difficult because it includes: temporal choices (shifting activities to different times of the day and/or different days of the week), activity choice (for example, shifting activities indoors), location choice (for example, moving), and climate neutralizing technologies (for example, using an air conditioner). Furthermore, the labor supply may further decline if a rise in morbidity from climate change forces individuals out of the labor force, or a rise in mortality from climate change decreases the potential labor force (Fankhauser and Tol, 2005).

Fifth, higher temperatures, increased intensity of storms, rising sea-levels, and tipping point events will increase the capital depreciation rate through losses of the capital stock and decreases in the longevity of capital (Hall and Behl, 2006; Fankhauser and Tol, 2005). Losses in capital stock are likely to result from sudden changes, such as from storms and tipping points, rather than slow changes that would allow for adaptation via the movement of capital (Hall and Behl, 2006). For example, Freeman (2000) cites potential capital stock losses of 1 percent, 5 percent, 12 percent, and 31 percent for a one in 10-, 50-, 100-, and 500-year storm, respectively, for Honduras. Another example is Hurricane Andrew and Hurricane Iniki in 1992, which combined to reduce the U.S. capital stock by \$55 billion (Cashell and Labonte, 2005). While the overall economic effect of natural disasters is debated (due to positive effects of reconstruction and remittances), it is clear that storms negatively affect growth through declines in the capital stock and that larger storms (which are more common under climate change) have overall negative effects (Fomby, Ikeda, and Loayza, 2011; Hochrainer, 2009).⁶⁴

Sixth, climate change could also affect economic growth via the capital stock through investment decisions. On the one hand, climate change could influence the relative prices of investment and consumer goods. Climate change is expected to affect a variety of market sectors that produce consumer goods and is generally expected to raise prices and decrease output in these sectors. Higher prices for consumer goods and lower levels of per capita output would lead to lower levels of consumption, while increased future prices could influence investment levels upward (Jorgenson et al., 2004). On the other hand, climate change could lower the amount of output available for investment, which would decrease the amount of capital via capital accumulation. Furthermore, decreases in the labor force and population from climate could decrease the amount of savings available for investment (Fankhauser and Tol, 2005).

Seventh, forward-thinking agents may also change their investment decisions due to the expected effects of climate change. However, it is unclear in which direction. On the one hand, forward-thinking agents may invest more now due to expected declines in future incomes. On the other hand, they may invest less due to lower expected returns on investments (Fankhauser and Tol, 2005; Moyer et al., 2013).

Eighth, increases in temperature may decrease capital productivity if we believe that the electricity grid becomes more unreliable with climate change. Ninth, according to Fankhauser and Tol (2005), Scheraga et al., (1993) argue that climate change could have structural effects on the economy by changing the relative size of sectors. This could have an effect on the composition of GDP. Tenth, the combination of declining tax revenue, due to declines in output, and increased investment in adaptation could decrease non-adaptation investments that grow the economy. In other words, climate change adaptation, particularly in terms of restoring or producing lost ecosystem services, drains capital and labor from research and development (Fankhauser and Tol, 2005; Moyer et al., 2013).

Last, an argument can be made for adding land to the production function. While this is not an input into production in the neoclassical growth model, it is one of the three factors of production in most political-economic work that predates the marginal analysis revolution. This would add additional channels through

which climate change could affect economic growth: declining land due to sea level rise and the loss of ecosystem services. This would allow for the loss of ecosystems to have more than a temporary effect on the economy.

Only DICE can be easily modified to capture these changes in growth. In FUND and PAGE (and DICE in the IWG analysis), it is difficult to model changes in the GDP growth rates due to climate change because economic growth rates are determined by an exogenous socio-economic scenario, as discussed above. In these models, the inclusion of the effects of climate change would require a change in the socio-economic scenario; this would make modeling the marginal effects of an additional unit of CO₂ more difficult. However, it is possible.

Modeling the effects of climate change on economic growth in an endogenous growth model, like DICE, is much easier although it requires the specification of a particular mechanism through which climate change may affect growth. As discussed above, DICE, as specified by Nordhaus and not IWG, is the only one of the three IAMs to use an endogenous growth model to estimate climate damages. DICE, as originally intended by Nordhaus, examines climate change using a variation of the Cass-Koopmans model with a single good that can be used for either consumption or saving/investment.⁶⁵ However, while DICE does allow for endogenous economic growth, all shocks are to consumption via a general shock to GDP; there are no shocks to labor, capital, or total factor productivity. Thus, modeling the effects of climate change on economic growth via the mechanisms discussed above will require modifications of DICE's structure. As currently specified, the endogenous economic growth structure of the DICE model, which allows for capital investment through an increased savings rate and investment in carbon abatement, allows for some mitigation of climate damages via: (1) increased capital investment that can offset climate damages to output, and (2) substitution of consumption for a reduction in carbon emissions (Nordhaus, 2011; Nordhaus and Sztorc, 2013).⁶⁶

Moyer et al., (2013) modifies DICE-2007 in two different ways to capture the effect of climate change on total factor productivity corresponding to the Cobb-Douglas production function that represents global economic output. First, Moyer et al., (2013) modify DICE such that a portion of climate damages affects the level of total factor productivity. As a consequence, climate damages affect output and economic growth. The authors find that even a small diversion of damages to total factor productivity can produce negative economic growth rates, such that even one-quarter of damages affecting total factor productivity can result a devastatingly high social cost of carbon dioxide of \$1,600. Second, they modify DICE such that climate damages reduce the growth rate of total factor productivity. As specified, total factor productivity cannot shrink as to produce economic contractions, and instead is limited to stalling economic growth. While this specification of the damage function does not result in economic collapse from climate change, like the previous specification, it implies an unequivocal increase in the SCC. From these results, Moyer et al., (2013) conclude that modeling the effects of climate change on economic growth can be as important as the discount rate in determining the magnitude of the SCC.

Two alternative IAMs, ENVISAGE and ICES, model the effects of climate change on economic growth (via shocks to labor, capital, and total factor productivity) in a general equilibrium model, GTAP. The authors of ENVISAGE model several damage sectors: agricultural, sea level rise, water, tourism, energy demand, human health and heat-related labor productivity.⁶⁷ Unlike DICE, FUND, and PAGE where climate damages affect consumption directly, climate change affects economic output through effects on labor, capital, and land productivity and stock, multi-factor productivity (that is, total factor productivity), and energy and tourist demand (Van der Mensburgghe, 2008). Depending on the damage sector, these shocks to productivity, input availability, and consumer demand can be heterogeneous and homogenous across economic sectors, that is, economic activities (Van der Mensburgghe and Roson, 2010). Using ENVISAGE, Roson and van der Mensbrugghe (2010) estimate damages of 1.8 percent and 4.6 percent of global GDP for increases of 2.3 degrees Celsius and 4.9 degrees Celsius,



Gonaïves, Haiti, after the hurricanes. Photo: Roosevelt Pinheiro/ABr

respectively, above 2000 temperatures; as noted earlier, labor productivity accounts for about 84 percent of total global damage in 2050 and 76 percent in 2100 (Roson and van der Mensbrugghe, 2010). The authors of ICES model several damage sectors: agricultural, sea level rise, forestry, floods, tourism, energy demand, and human health.⁶⁸ In ICES, damages affect economic activity through supply side shocks to capital and land stocks and capital, labor, and land productivity (Bosello, Eboli, and Pierfederici, 2012). Like ENVISAGE, the authors of ICES also model demand shocks to tourism and energy demand in addition to supply shocks. Bosello et al., (2012) estimate a 0.5 percent decline on global GDP for a 1.9 degrees Celsius increase in global temperatures relative to pre-industrial temperatures.

Non-market damages

Yohe and Tirpak (2008) and Tol (2009) note that many non-market damages are still missing from current estimates and need further study. Among these are the non-market impacts of ocean acidification (as mentioned earlier), the loss of ecosystem services, the loss of biodiversity, and the omission of some health costs (Tol, 2009). While not an omitted damage per se, the default versions of the IAMs also fail to capture the increase in the value of non-market commodities relative to market goods due to their increase in scarcity. This failure results in a systematic underestimation of non-market damages, particularly biodiversity and ecosystem services, as the value of losses increase.⁶⁹

ECOSYSTEM SERVICES. Natural ecosystems provide a multitude of services that benefit humanity, which are collectively known as ecosystem services. Many of these services are essential for human existence. The United Nations Millennium Ecosystem Assessment groups ecosystem services into four types: (1) provision (food—crops, livestock, fisheries, aquaculture, wild plant and animal products; fiber—timber, cotton, hemp, silk, wood fuel; genetic resources; biochemical, natural medicines, and pharmaceuticals; ornamental resources; fresh water), (2) regulating (air quality regulation; climate regulation—global, regional, and local; water regulation; erosion regulation; water purification and waste treatment; disease regulation; pest regulation; pollination; natural hazard regulation), (3) cultural (cultural diversity; spiritual and religious values; knowledge systems; educational values; inspiration; aesthetic value), and (4) supporting services (soil formation, photosynthesis, primary production, nutrient cycling, and water cycling). The ecosystems that provide these services are known as natural capital; their value equals the present value of all future streams of ecosystem services.

By the end of the century, climate change will be the most important driver of natural capital loss, ecosystem change, and ecosystem service loss. While some regions may experience some initial benefits from climate change in terms of increased ecosystem service provision, overall, the globe will experience negative effects and eventually all regions will experience losses (Millennium Ecosystem Assessment; IPCC, 2007). While not all services are affected by climate change, many of them are. Of these services, only a few are currently included in the IAMs.

Some ecosystem services are already accounted for in the social cost of carbon via other damage sectors. Some of these ecosystem services are explicitly captured by all three IAMs. For example, food and fiber services (particularly crops, livestock, and timber) are explicitly captured via the agricultural, forestry, and “other market” sectors.⁷⁰ Some ecosystem services are only captured by some IAMs. For example, only PAGE09 and early versions of DICE explicitly include climate regulation services (particularly globally) in their estimates of the social cost of carbon via their tipping point and catastrophic damage functions, respectively; see the catastrophic damage section below for further discussion.⁷¹ Finally, some ecosystem services are clearly excluded from the default versions of current IAMs, such as pest regulation and pollination as discussed earlier.⁷² Some of these omitted services can be thought of as examples of inter-sector services from the non-market sector to the market sector, and will be discussed indirectly in the subsection on the omission of inter-sector damages.

It can be difficult to determine whether ecosystem services are already captured via existing damage functions for two reasons. First, whether an ecosystem service is captured in the damage function(s) is dependent on whether the source of the damage estimate accounted for this service. For example, it could be potentially argued that water purification and water cycling services of ecosystems are already captured in FUND and early versions of DICE (and thus PAGE09, which includes estimates from both other IAMs) via the water sector and the “other market” sectors, respectively. However, this is only true if the water purification and cycling services of ecosystems are directly measured by the underlying studies used to calibrate these models, and this is not the case. In the case of water purification services, forested catchments supply 75 percent of the globe's fresh water supplies (Shvidenko et al., 2005; IPCC, 2007 – Chapter 4), and these services could potentially be accounted for in the underlying forestry damages. While the forestry sectors in both models account for the effect of climate change on the value of timber sales, the water sector (within the “other market” sector in DICE-1999) fail to explicitly account for the water purification services of ecosystems. Thus, none of the three IAMs are likely to capture the effect of climate change on the water supply via its effect on forest ecosystems.⁷³

Second, some of these omitted services, including water purification and cycling services, may be captured in general attempts by IAMs to capture the value of natural capital. In FUND 3.5 to 3.8, ecosystem damages from climate change are based on a “warm-glow” effect whereby the population's valuations of damages are independent of any real change in ecosystems (Anthoff and Tol, 2012). The warm glow effect is measured by how much people say they are willing to pay for services resulting from habitat preservation services (for example, to preserve wildlife), and Tol (2002) explains that the effect “suggest that people's willingness to pay reflects their desire to contribute to a vaguely described ‘good cause,’ rather than to a well-defined environmental good or service.” However, Anthoff and Tol (2012) calibrate the ecosystem damage function to estimates from Pearce and Moran (1994), who report a mean willingness to pay of \$50 per person in OECD nations for habitat. While Pearce and Moran use the \$50 value to specifically value loss of habitat services (for example, to preserve species), FUND generalizes this figure to be a warm-glow valuation of people's willingness to contribute to the environment as a societal good. However, this extrapolation is not valid: Tol excludes many of the non-habitat services of ecosystems from FUND because these estimates are based on provision of habitat services

by ecosystems and not the other tangible and intangible ecosystem outputs.⁷⁴ Therefore, FUND likely omits the value of many ecosystem services.

Alternatively, Nordhaus and Boyer (2000) use their own discretion to determine regional economic damages from climate change to ecosystems in DICE-1999 (also one of the sources used to calibrate the default version of PAGE09); the authors develop their own rough estimates of the loss of natural capital because of the highly speculative nature of estimates. The authors assume that the capital value of the portion of human settlements and ecosystems sensitive to climate change is between 5 percent and 25 percent of regional GDP depending on their size, mobility, and robustness and sensitivity. It is further assumed that a region's annual willingness to pay to prevent climate damages to human settlements and ecosystems equals 1 percent of their capital value, "which is one-fifth of the annualized value at a discount rate on goods of 5 percent per year (Nordhaus and Boyer 2000)." Therefore, the default version of PAGE09 partially captures some of these "omitted" ecosystem services. However, it is impossible to tell to what extent because (1) the PAGE09 default damage functions are also greatly informed by damage estimated from FUND, in addition to DICE-1999, which potentially only captures the value of habitat services (as discussed in previous paragraph), and (2) it is impossible to tell what damages to ecosystem services are omitted from the DICE-1999 climate damage estimates because of the speculative nature of this valuation.

In DICE-2013, the value of natural capital is likely excluded (or at best partially captured) due to a failure of many of the underlying studies to consider them, particularly the studies that only capture market damages.

BIODIVERSITY. The habitat services of ecosystems may or may not include the value of biodiversity in some IAMs. By the end of the century, climate change will be the single most import driver in biodiversity loss (Millennium Ecosystem Assessment). According to the IPCC (2007), "approximately 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C." Given the significant species loss that could occur by the end of the century and the likelihood of continued biodiversity loss with even higher temperatures thereafter, accurate estimates of the value of biodiversity loss are essential.

Tol (2009) considers biodiversity loss to be among the largest of the omitted impacts of climate change. Economists not only struggle to place a value on biodiversity, but they also lack the understanding of how climate change will affect intricate systems and processes like nutrient cycles. Furthermore, rather than occurring more gradually as does sea level rise, biodiversity loss is likely to be characterized by a series of system failures and ecological shocks, making it even more difficult to model (Tol 2009). Thus, current default versions of the IAMs may be omitting the value of biodiversity loss. This statement may seem inconsistent with Tol's FUND model given the inclusion of biodiversity loss in FUND 3.6, as a function of species loss (that is, the value of biodiversity increases with the loss of species) and temperature change. However, Tol (2009) is essentially arguing that future work is necessary to improve the accuracy of the estimate of the value of biodiversity, and he will continue to use the warm glow effect (as discussed in the previous section) in FUND until a better estimate becomes available.^{75,76}

Like ecosystem services in general, it is unclear how extensively the default versions of the other two IAMs, DICE-2013 and PAGE09, account for biodiversity. These are for the same reasons as discussed in the previous subsection.

OMITTED HEALTH COSTS. According to Tol (2002a), morbidity and mortality can be directly influenced by climate in six ways: (1) high and low temperature (that is, heat and cold stress), (2) vector-borne infectious disease (3) non-vector-borne infectious disease (including, zoonotic and waterborne diseases (NIH 2010) (4) air quality, (5) floods and storms, and (6) inter-sector effects of agriculture and water quality. A seventh path of influence, which is missed by Tol (2002a), is humanity's socially contingent response to climate change, including forced migration, political and civil unrest, and increased violence.

None of the three IAMs discussed by the IWG includes all categories of damages. DICE-1999, which is utilized as a damage source in the default version of PAGE09, focuses on air pollution and the expansion of the geographical distribution of tropical diseases, including vector-borne diseases (malaria, dengue fever, trypanosomiasis, Chagas disease, schistosomiasis, leishmaniasis, lymphatic filariasis, and onchocerciasis) due to higher temperatures (Nordhaus and Boyer, 2000). Second, FUND 3.6, earlier versions of which were also utilized as a damage source in the default version of PAGE09, captures mortality and morbidity from four sources: diarrhea, vector-borne diseases, cardiovascular and respiratory disorders, and storms (Anthoff and Tol, 2012). Within the causes of health damages considered in FUND, however, modeling assumptions omit relevant damages. For example, heat-related cardiovascular mortality and morbidity is limited to urban areas, but we see no reason to ignore these effects within rural populations (Ackerman, 2010). Additionally, "the total change in mortality is restricted to a maximum of 5% of baseline mortality (per cause)" (Anthoff and Tol, 2012); under high levels of warming (for example, 6 degrees Celsius), this may be an unjustifiable restriction that will bias social cost of carbon estimates downward. Last, it is unclear what health damages are included in DICE-2013 because of its meta-analysis structure, and because several studies utilized in the analysis rely on statistical methods that are less explicit in what types of health costs are captured.

Early versions of DICE, upon which the default version of PAGE09 is partially based, and recent versions of FUND are not consistent in what types of health damages are included. On the one hand, DICE-1999 excludes many negative health effects of climate change captured by FUND: diarrhea (fourth and eleventh leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez [1997]), cardiovascular disorders, respiratory disorders, tropical storms (hurricanes and typhoons), and extra-tropical storms (cyclones). Additionally, DICE fails to account for the cost of morbidity. On the other hand, FUND fails to account for declining air quality due to pollution that results from climate change, some of which DICE-1999 captures.

There are many health effects that DICE or FUND, and thus likely PAGE, omit. This includes: mortality and morbidity from the combined effects of storms and rising sea levels (that is, coastal flooding), flooding more generally (inland flooding from flash floods and the overflow of rivers), mortality, morbidity and air pollution effects from forest fires, non-vector-borne infectious diseases, some vector borne infectious diseases (like Lyme disease), and decreased air quality due to pollination; decreased labor productivity due disease and increased heat (see the subsection above of the effects of climate change on the economic growth rate for further discussion); and indirect health damages from climate change via agriculture and water resources (Ackerman and Munitz, 2012; Hanemann, 2008; IPCC, 2007; Tol, 2002; WMO, 2006). Finally, violence (the 16th and 14th leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez, 1997) and war injuries (the 20th and 15th leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez, 1997) may increase if social conflicts arise due to climate change.

There are also general equilibrium effects of health damages that are omitted by the IAMs. Tol (2009) referring to the results of his own paper, Bosello, Rosen, and Tol (2006), states that "the direct costs are biased towards zero for health, that is, direct benefits and costs are smaller in absolute value than benefits and costs estimated by a

general equilibrium model. This is because countries that would see their labor productivity fall (rise) because of climate change would also lose (gain) competitiveness, so that trade effects amplify the initial impact.” Therefore, the exclusion of these general equilibrium impacts may further bias the health damages included in IAMs further downwards.

RELATIVE PRICES. Climate change is predicted to affect market and non-market goods produced outdoors (such as agricultural, fisheries, forestry, and environmental goods and services) more than market goods produced indoors; market goods insensitive to climate change account for the majority of GDP (Nordhaus and Boyer, 2000). As a consequence, outdoor produced goods will become relatively scarcer than indoor produced goods over time. Based on the law of scarcity, the value of outdoor produced goods and services will increase relative to indoor produced market goods. However, current damage estimates to climate sensitive goods and services reflect the current ratio of their economic value to climate insensitive goods, which is based on the current ratio of their quantities. By extrapolating these estimates to future time periods without making any explicit adjustment for relative prices, that is, without accounting for relative change in value of outdoor produced goods and services to indoor produced goods over time, the developers of IAMs implicitly assume constant relative prices, and bias the SCC downward.

A methodically sounds way to address this issue is to explicitly model relative prices. However, most IAMs (including DICE, FUND, and PAGE) include only an aggregate consumption good, as measured by per capita consumption, in the social welfare function.⁷⁷ On the consumer side of the economy, this assumption implies all goods and services, including market goods and non-market goods, are perfectly substitutable (even in the long-run), and that they have constant relative prices (Gerlagh and van der Zwaan, 2002; Sterner and Persson, 2008). Constant relative prices imply the ratio of the prices of any two goods must remain constant, regardless of the amounts available of either good.⁷⁸ As a consequence, the current IAMs fail to capture the increase in value of outdoor produced goods and services relative to other traditional consumption goods produced indoor (Gerlagh and van der Zwaan, 2002; Sterner and Persson, 2008).⁷⁹ Therefore, the simplifying assumption of modeling only one generalized consumption good biases the social cost of carbon estimates downward because future damage estimates to climate sensitive goods and services fail to account for the increase in relative value of these goods and services, as discussed in the previous paragraph.

Recent work has looked at the effect of disaggregating per capita consumption into market goods and non-market goods. Developing a simple social welfare function with two sectors (market and non-market) that grow at different rates, Hoel and Sterner (2007) find that increasing consumption of market goods and constant or decreasing consumption of environmental services will increase the relative value of environmental services due to their increasing relative price when the elasticity of substitution is less than one, that is, it is difficult to substitute market goods for non-market goods.^{80,81} Hoel and Sterner (2007) demonstrate, as Gerlagh and van der Zwaan (2002) did before them, that the value of market goods will collapse to zero in the long run if these paths continue. After deriving an updated equation for the discount rate (similar to the Ramsey equation) resulting from the new specification, Hoel and Sterner (2007) also find that the combined effect of a newly derived discount rate and the change in relative prices can result in damage estimates that exceed those calculated under traditional discounting.⁸² The work in Hoel and Sterner (2007) applies to any two sectors of the economy, not just market and non-market goods.⁸³

To capture these effects on the optimal emissions path, Sterner and Persson (2008) modify DICE to restrict substitutability between non-market and market goods. Like Hoel and Sterner (2007) and Neumayer (1999) before them, Sterner and Persson (2008) find that allowing a change in relative prices can increase the costs

of climate change relative to a model assuming constant relative prices. More specifically, the authors find that damages double from 1.05 percent of GDP for a 2.5 degree Celsius increase to 2.1 percent of GDP; this implies that the SCC would also increase with a switch away from constant to relative prices. Using their base parameters, Sterner and Persson (2008) also find that allowing for a change in relative prices achieves a lower optimal emissions path than the Stern Review (Sterner and Persson, 2008; Heal, 2009).⁸⁴ In this sense, relative prices can be as important as the discount rate in determining the optimal climate change prevention policy. However, their results are highly dependent on the assumed elasticity of substitution. The lower the actual elasticity of substitution is, that is, the more difficult it is to substitute market goods for lost non-market goods to make society as equally well off under climate change, the more likely the current integrated assessment models are to underestimate the environmental cost of climate change by assuming perfect substitutability.

As is common in these models, we are left with uncertain parameters determining the optimal level of conservation. In this particular case, this is the elasticity of substitution. This recasts the argument about whether or not to act now from a disagreement about the discount rate into a debate of whether poor (strong) sustainability or perfect (weak) sustainability, that is, an elasticity of substitution less than or greater than 1 in the context of the CES utility function, holds in the long run (Gerlagh and van der Zwaan, 2001). Unlike the pure rate of time preference and the elasticity of the marginal utility of consumption, the elasticity of substitution is not an ethical parameter. However, there is still considerable uncertainty about this parameter due to a lack of empirical data (Neumayer, 1999). Sterner and Persson (2008) argue that a lower elasticity of substitution is more likely because some environmental goods are unique and irreplaceable (for example, drinking water), and these goods are likely to dominate the calculation of the elasticity of substitution as environmental goods become more scarce. In a similar argument, Heal (2009) states that market goods and environmental services are complements because some of the services in the former group are irreplaceable and essential to life (Heal, 2009; Dasgupta and Heal, 1979). Heal (2009) points out that this has two implications: some level of environmental services is essential and that the elasticity of substitution is not a constant.⁸⁵ Gerlagh and van der Zwaan (2002) demonstrate that even if the substitutability varies with the amount of environmental services, there often exists a level of environmental services below which poor substitutability occurs in the long run. While these arguments support an elasticity of substitution below which it is difficult to substitute consumption goods for environmental goods (elasticity of substitution of less than one), future debate is likely to ensue as current statements are more a matter of belief due to a lack of empirical evidence (Neumayer, 1999).



Greenland ice loss exceeds that of Ice gain. Photo:Christine Zenino, Chicago, US

All three IAMs include only an aggregate consumption good in the social welfare function, and so assume constant relative prices and perfect substitutability. While FUND 3.6 does account for the increase in the relative value of habitat services due to the loss of species, this is done in a limited way. Therefore, all three IAMs systematically underestimate climate damages to non-market commodities, possibly by a large margin.

Socially contingent damages

Many social scientists and economists have argued that the ill-effects of damages to commoditized goods from climate change will extend beyond the calculated loss of value to affect societal dynamics (U.S. Climate Change Science Program, 2008). For example, agricultural damages account for the value of diminished productivity and lost crops, but not for the social repercussions of food insecurity and famine. In many regions, shifting weather patterns, rising sea levels, and increased natural disasters will threaten infrastructure, habitable lands, crop yields, and water resources. Under the resulting intensified resource competition, individuals will have to choose among adapting to resource scarcity, relocating to a region with more abundant resources, or using force to secure a share of the available resources. Each coping pathway has implications for political and social stability (Buhaug, Gleditsch & Theisen, 2009).

The IPCC, which once included social consequences (such as migration) as direct consequences of climate change, has since revised its stance, focusing instead on “human vulnerability,” a measure expressing the relative risk of welfare impacts of climate change for individuals and communities (Raleigh & Jordan, 2010; IPCC, 2001). Vulnerability is determined both by physical factors (for example, drought likelihood) and social factors (for example, social status). Highly vulnerable societies are less likely to succeed in their adaptation efforts, and consequently, more likely to resort to conflict and migration. Adaptation strategies used in poorer regions such as removing children from school to provide additional income or subsisting on fewer resources, diminish the welfare of those employing them, and thereby increase the incentives for migration or armed conflict over time. Homer-Dixon (1999) argues that the developing world is more vulnerable to resource scarcity because the “innovation gap”—the difference in capacity between those who are able to innovate solutions to resource scarcity and those who are not—is largely dictated by the financial, physical, and human capital stores and the capacity to mobilize them. As a consequence, developing countries are much more likely to be susceptible to social and political instability from climate change (Homer-Dixon, 1999).

The study of climate change’s social impacts is still emerging despite a lack of ability to predict their severity or likelihood. The risks of these broader, complex social responses to climate change are poorly understood and difficult to anticipate, and historical studies are of little use given the unprecedented nature of climate change. In particular, because climate change is a contributing factor and not the direct cause of migration and conflict, isolating the role and corresponding social damages of climate change is especially difficult (Homer-Dixon, 1999; Buhaug, Gleditsch & Theisen, 2008). In addition, the identification strategies of many papers are confounded by various statistical difficulties (Dell, Jones, and Olken, 2013).

Partially as a result of this difficult identification problem, the most recent versions of the three IAMs used by IWG do not address socially contingent damages, such as migration, social and political conflict, and violence. The one exception is FUND, which partially accounts for this social cost indirectly by modeling migration from permanent flooding. However, as discussed under inter-regional damages, FUND ignores most of the costs of migration, including the social conflict caused by an influx of migrants.

MIGRATION. Increases in labor migration and distress migration are likely results of increasing temperatures, reduced rainfall, shorter growing seasons, and sea level rise. Labor migration, generally driven by the “pull” force of economic opportunity, is common in many societies and can play an important role in the adaptation of communities by diversifying income sources and providing supplemental income through remittances. Distress migration, driven by the “push” force of local calamity, tends to be a coping mechanism of last resort. Labor migration is particularly sensitive to climate change-related factors, especially those that are gradual or chronic, which increase the need for income diversification and the allure of economic opportunities elsewhere. Distress migration only increases under sudden shifts, such as natural disasters (for example, severe storms) or irreversible changes (for example, permanent flooding from sea level rise). Distress migration is also more sensitive to social factors than labor migration. The ease of evacuation and availability of relief affect the rates of distress migrations, while community support, economic opportunities, and governmental policies influence resettlement rates. The severity and permanence of damage also play important roles in determining rates of migration and relocation (Raleigh & Jordan, 2010).⁸⁶

It should be noted that mass migration, as predicted by many analysts, may also have significant effects on non-market goods and services. Specifically, mass migration into lesser affected areas may result in damages to environmental goods and services to the incoming nations (Oppenheimer, 2013). This type of damage would qualify as an inter-sector effect, which is discussed in a following section.

CONFLICT. In large scale crises, such as climate change, conflict tends only to occur in societies with histories of armed violence and deep political and social fragmentation. The developing world, which is slated to bear the brunt of climate change due to a lack of adaptive capacity, is considered especially vulnerable to climate-change-related social crises because their economic and political institutions tend to be less stable than those of the developed world (Millner & Dietz, 2011; Buhaug, Gleditsch & Theisen, 2008). Lower availability of financial resources and insurance also tend to increase the rate and permanence of climate change damages in developing countries, making conflict more likely, and intensifying existing conflicts (Millner & Dietz, 2011).

Buhaug, Gleditsch and Theisen (2008) advance four narratives on how climate change can drive conflict by contributing to political instability, economic instability, migration, or inappropriate governmental response. Climate change can exacerbate political instability when weak political institutions fail either to adequately address climate-related catastrophes (droughts, famines, and so on) or to deliver other public goods (such as healthcare, education, and infrastructure) because remediating such catastrophes diverts significant resources. Climate change can contribute to economic instability when decreased availability of a renewable resource drives down household incomes, which can compound existing intergroup inequalities and reduce the governmental funds available to adapt to climate change.⁸⁷ Migration driven by natural disasters or sea level rise could cause influxes of climate refugees, increasing environmental, economic, social and political stresses in receiving areas, particularly when the incoming refugees are of a different nationality or ethnic group. Finally, unpopular responses to climate change, such as draconian emission reduction mandates, could result in social uprisings in response. Dell, Jones, and Olken, (2013) also highlights the possibility that weather can directly lead to conflict through “changing the environment” or increasing human aggression.

There is literature studying the effect of weather and social and political conflict that is summarized quite thoroughly in Dell, Jones, and Olken (2013). In particular, there are a variety of cross-country and subnational studies which indicated that higher temperatures and lower-than-average precipitation (including droughts) cause civil conflicts and political instability (for example, coups), particularly via the lower household income mechanism. While there are various studies showing the effect of weather on social and political conflict, there

is some ambiguity in the effect because of (1) the low explanatory power of weather of conflict (that is, the noise), (2) a variety of statistical problems, including endogenous controls and spatial correlation, (3) the difficulty of measuring weather, particularly precipitation due to the negative effect of too much (for example, floods) and too little (for example, droughts), and (4) the difficulty of determining if weather changes the timing of conflict or actually causes conflict.

Two important recent papers identifying the connection between climate change and social and political conflict are: Hsiang, Meng, and Crane (2011) and Hsiang, Burke, and Miguel (2013). Hsiang, Meng, and Crane (2011) use more than 50 years of data to show that the probability of conflict doubled in the tropics during El Niño years as compared with La Niña years. Based on their analysis, El Niño contributed to 21 percent of the civil conflicts in the tropics taking place between 1950 and 2004, providing some evidence that warmer temperatures do result in more social conflict. This paper is important in that it provides evidence that weather caused more conflict, and displaced only a portion of conflicts over time.⁸⁸

In another study, Hsiang, Burke, and Miguel (2013) conduct a meta-analysis across 60 multi-disciplinary papers.⁸⁹ The authors find that the median effect of a 1-standard-deviation change in climate variables over time causes a 13.6 percent change in the risk of intergroup conflict and a 3.9 percent change in interpersonal violence.^{90,91} Similarly, precision-weighted average effects, in which studies were down-weighted based on their precision, are 11.1 percent and 2.3 percent, respectively. Even though the magnitude of this effect is heterogeneous (that is, varies over time and space), given that scientists predict a 2- to 4-standard-deviation change in temperature by 2050, possible increases in conflict as the result of climate change are likely to be significant this century in many areas across the globe. In general, the authors find that all types of conflict increase with temperature and precipitation, regardless of the temporal scale, but intergroup violence is less common in rich countries than poor countries.⁹² Furthermore, the evidence indicates that adaptation possibilities are limited in that slow-moving climate change still adversely affects conflict, and these effects will continue into the next century. While the authors note that several avenues are possible to connect climate change to social conflict, more research is necessary to select between competing theories on these linkages.⁹³ Additionally, it is still unclear whether these mechanisms increase the probability of a conflict occurring or the probability of an existing conflict becoming violent.

VIOLENCE AND CRIME. Dell, Jones, and Olken (2013) review the literature studying the effect of weather on violence. In the criminology literature, there is a well-known relationship between higher temperatures and crime, particularly as it relates to aggression. Specifically, many authors find that higher temperatures increase criminal activity, especially as it relates to violent crime. There is an ongoing debate within the literature on whether the cause is neurologically based or a socially contingent response. With respect to precipitation, there is more of a mixed result with some evidence that a lack of precipitation may increase crime and violence through a channel of lower income.

Catastrophic climate change

There is agreement within the literature on the importance of catastrophic damages. However, there is significant debate within the literature about the extent of their importance; see earlier discussion. Regardless of the side one takes, it is clear that these catastrophic damages should be included in IAMs, and the current failure to do so in some IAMs biases their SCC estimates downward. Given Hope's (2013) finding that tipping-point damages can be as important as the sum of economic damages included in IAMs in determining the social cost of carbon, these biases may be significant.

TIPPING POINTS. The IAMs differ in their treatment of climate tipping points. Earlier versions of DICE, that is, DICE-1999, DICE-2007, and DICE-2010, include certainty equivalent damages of catastrophic events as estimated in a survey of experts in Nordhaus (1994a).⁹⁴ For the most recent version of the model, that is, DICE-2013, Nordhaus moved to a meta-analysis based on estimates in Table 1 of Tol (2009). Most of these sources do not include tipping point damages, and it is unclear to the extent that they are included in these newer versions of DICE.⁹⁵ While DICE-2013 does include the possibility to explicitly model catastrophic damages, it is excluded from the default version of the model (correspondence with Nordhaus).⁹⁶

PAGE explicitly models tipping points in the default version of his model. From PAGE2002 to PAGE09, Hope moved from modeling discontinuous impacts using certainty equivalence to modeling them as a singular, discrete event that has a probability of occurring in each time period when the realized temperature is above a specified temperature threshold (with a central value of 3 degrees Celsius in the default version of the model), and this probability is increasing in temperature. Of the recent versions of the three models, only PAGE09 fully explicitly models tipping point damages; still a risk premium for aversion to such an event is generally not included in the default versions of IAMs (Kouskey et al., 2011).

While PAGE09 and early versions of DICE explicitly model tipping point damages, an alternative, as represented by Lemoine and Traeger (2011), is to implicitly capture tipping point damages by explicitly modeling tipping points. As stated by the authors, they “directly model the effect of a tipping point on climate dynamics rather than approximating its effects by shifting the damage function.” Specifically, Lemoine and Traeger (2011) model two broad types of climate tipping points within DICE: (1) increased climate sensitivity (that is, the increase in global surface temperature from a doubling of the CO₂ concentration in the atmosphere) due to increased strength in climate feedback effects beyond current predications, and (2) increased greenhouse gas atmospheric longevity beyond current climate models.⁹⁷ It should be noted that this is distinct from modeling fat tails because these modeling changes do not require the use of fat-tailed distributions.

In a similar way, FUND implicitly models tipping points by explicitly modeling the uncertainty of almost 900 parameters in the FUND model.⁹⁸ According to Anthoff and Tol (2013a), this captures catastrophic damages more generally by capturing the possibility of catastrophic outcomes, that is, welfare effects. It is unclear to the extent that this method captures tipping points as evidenced by the decision by Hope to jointly model parameter uncertainty and a catastrophic damage function in PAGE09. In other words, FUND may not sufficiently capture catastrophic damages via climate tipping points by simply modeling the uncertainty underlying all parameters in the model.

FAT TAILS. The popular IAMs differ in their ability to capture the catastrophic damages that result from fat tails. However, for the most part, those IAMs fail to model fat tails as suggested by Weitzman. This is because “numerical model(s) cannot fully incorporate a fat-tailed distribution (Hwang, Reynès, and Tol, (2011)).”

On the one hand, both FUND and PAGE explicitly model the uncertainty of model parameters by specifying parameter distributions and run Monte Carlos simulations.⁹⁹ However, neither model explicitly chooses fat-tailed distributions in its default version. Hope chooses triangular distributions, which explicitly specify minimum and maximums for the probability distribution function, for many of the uncertain parameters in the default version of PAGE; the exception is the climate sensitivity parameter which follows the IPCC (2007) report. In FUND, Tol tends to choose triangular and gamma distributions; the gamma distribution is thin tailed (Weitzman, 2009).¹⁰⁰ However, while Anthoff and Tol (2013a) do not explicitly utilize fat-tail distributions to represent the probability distributions of their 900 uncertain parameters, the distribution of net present welfare

from a Monte Carlo simulation of 10,000 runs of FUND 3.6 is fat tailed.¹⁰¹ While fat tails arise in the distribution of welfare in the FUND model, explicitly modeling parameter distributions as fat tailed may further increase the SCC.

On the other hand, the default versions of the DICE models fail to model any parameter uncertainty. As a consequence, the default versions of all DICE models fail to capture catastrophic damages via the fat tails of uncertain parameters. This is particularly significant when parameters have a right-skewed distribution, such as the climate sensitivity parameter and the possible discontinuity outcomes. Therefore, DICE-2013 mostly excludes catastrophic damages via tipping points and fat tails when parameter uncertainty is ignored.

There have been several attempts to include fat-tailed distributions in the popular IAMs. First, Hwang, Reynès, and Tol (2011) found an increase in the optimal carbon tax when accounting for fat tails in DICE; the optimal carbon tax increases in the uncertainty of the climate sensitivity parameter. Similarly, Ackerman, Stanton, and Bueno (2010) find that fat tails over the climate sensitivity parameter increases the economic costs of climate change, and hence the SCC, in DICE, but the magnitude of this increase is highly dependent on the exponent of the DICE damage function. Second, Pycroft et al., (2011) replaces above the 50th percentile of the original triangular distributions for the climate sensitivity parameter and the damage function (sea level rise, market, and non-market) exponents in the PAGE09 model with thin-tailed (specifically, the normal distribution), medium-tailed (specifically, the log-normal), and fat-tailed (specifically, the Pareto) distributions;¹⁰² they switch off the catastrophic damage function when they modify the distributions of the damage function exponents, decreasing the PAGE09 SCC estimate from \$102 in the default version of PAGE to \$76, because tipping points and fat tails are related concepts, as discussed earlier in this paper. The authors find that the PAGE09 SCC estimate without a catastrophic damage function increases by 44 percent to 115 percent when medium and fat tails are integrated into PAGE09; this corresponds to an increase from \$76 to \$135 (thin), \$147 (medium), and \$218 (fat).¹⁰³ Larger percentage increases are observed for the 95th and 99th percentile SCC estimate. In other words, the use of fat-tailed distributions is possible and will significantly increase the social cost of carbon. At the same time, because its value is not infinite, as it is using Weitzman's Dismal Theory analysis, the SCC is still useful for benefit-cost analysis.

By explicitly modeling the probability distribution function of the climate sensitivity parameter using the Roe-Baker distribution, the 2013 IWG analysis may partially capture the effects of fat-tailed distributions; the Roe-Baker distribution used in this analysis is fat-tailed (Pindyck, 2013).

BLACK SWAN EVENTS. All three IAMs may exclude black swan events. While it is unclear how these events could be integrated into these models, it is clear that their exclusion biases SCC estimates downward because scientists believe that bad surprises are more likely than good surprises when it comes to climate change. As discussed earlier, these events may be captured by integrating fat-tail distributions for uncertain parameters into IAMs, but the “correct” fat-tailed distribution is still unknown.

Inter-sector damages

According to both Kopp and Mignone (2012) and the IWG (2010; 2013) IAMs fail to capture inter-sector damages, that is, damages from the interaction of damage sectors. There are a variety of potential inter-sector effects of climate change, and their omission generally tends toward a downward bias. Inter-sector damages include: agriculture and water quality on human health (Tol, 2009; IPCC, 2007); the effects of water supply and quality

on agriculture; the combined effects of increased storm strength and rising sea levels (Yohe and Hope, 2013); the effects of ocean acidification on human settlements; and the effects of ecosystem services on the market sector. As mentioned earlier, many of these inter-sector damages include damages that arise from the interaction of climate change effects between sectors in the market-, non-market-, socially-contingent-, and catastrophic-damage categories.

For the most part, the major integrated assessment models (FUND, PAGE, and DICE) calibrate their damage functions, and as a consequence estimate the social cost of carbon, using sector specific studies, or, at least, rely on studies that utilize sector specific damage estimates, that is, enumerative studies.¹⁰⁴ Implicitly, the authors of the IAMs assume that each sector is an island, independent of all other sectors. Therefore, inter-sector damages are captured by IAMs only if the underlying studies account for these inter-sector damages. For example, agricultural studies that account for the effect of climate change on precipitation and the water supply for irrigation will include the effects of the water supply sector on the agricultural sector. However, most damage studies are incomplete as they omit these inter-sector damages (Yohe and Hope, 2013).¹⁰⁵

The developers of PAGE and FUND argue that these models capture inter-sector effects. On the one hand, Hope (2006) argues that only inter-sector damages between market and non-market sectors, such as ecosystem services, are excluded. Specifically, he argues that all other inter-sector damages are captured because “PAGE2002 models two damage sectors: economic and non-economic. ... Using highly aggregated damage estimates from the literature allows PAGE2002 to capture interaction effects implicitly.” This is something of a tautology – that is, I utilize generalized aggregate damage functions, and because they are general, I capture interactions. As stated above, inter-sector damages can only be captured if the underlying damage estimates account for them, and they do not in the case of the default version of PAGE09. On the other hand, Tol (2009) goes even further by arguing that IAMs, such as FUND, may be double counting inter-sector damages. For example, the effect of water supply on the agricultural sector may be captured by both the water and agricultural sector damages.¹⁰⁶ Again, this can only be the case if the underlying studies explicitly account for these damages, and this is not the case in FUND due to its reliance on enumerative studies that do not account for inter-sector damages.¹⁰⁷

The latest versions of the three IAMs utilized by IWG omit inter-sector damages. FUND3.6 and DICE-1999 utilize sector-specific damage estimates (from enumerative studies), and by the arguments above omit most, if not all, of the inter-sector damages excluded from the underlying studies. Because PAGE09 is greatly informed by FUND and DICE-1999, it too omits these inter-sector damages even though it relies on aggregate market- and non-market-damage functions. Finally, DICE-2013 also omits most inter-sector damages. Of the 13 studies underlying the DICE-2013 meta-analysis, eight (Nordhaus, 1994a; Fankhauser, 1995; Tol, 1995; Nordhaus and Yang, 1996; Plambeck and Hope, 1996; Nordhaus and Boyer, 2000; Tol, 2002; Hope, 2006) of them rely on sector-specific calibration techniques (that is, rely on enumerative studies), and omit any inter-sector damages excluded from the underlying studies. Four of the remaining five studies (Mendelsohn, Schlesinger, and Williams, 2000; Maddison, 2003; Rehdanz and Maddison, 2005; and Nordhaus, 2006) utilize statistical technique to estimate the damages from climate change. While statistical methods can capture inter-sector effects, all four of these studies omit the damages from the interaction of market and non-market sectors; Maddison (2003) and Rehdanz and Maddison (2005) only include non-market damages, and Mendelsohn, Schlesinger, and Williams (2000) and Nordhaus (2006) include only market damages. Thus, like the other IAMs, DICE-2013 fails to account for many inter-sector damages.



Wind erosion is evident on this rangeland during severe drought in Arriba County, New Mexico.
Photo by Jeff Vanuga, USDA Natural Resources Conservation Service.

Cross-Sector Damages

As discussed earlier, many of the omitted effects of climate change comprise both market- and non-market-damage sectors. This section discusses omitted climate impacts that affect multiple categories of damages (as opposed to inter-sector damages, where multiple impacts interact to contribute to damages in a specific sector): market, non-market, socially contingent, and catastrophic damages. This includes inter-regional damages, destabilizers of existing non-climate stressors, weather variability and climate extremes, and ocean acidification.

INTER-REGIONAL DAMAGES. Inter-regional damages are spillovers from one region to another. For the most part, the major integrated assessment models (FUND, PAGE, and RICE) estimate the social cost of carbon assuming each region of the world is independent of all other regions. There are a variety of potential inter-regional effects of climate change, and their individual omissions may result in an upward or downward bias. While the individual biases are in both directions, Freeman and Guzman (2009) argue that the overall effect very likely leads to an underestimation of the SCC for the United States.

Freeman and Guzman (2009) lay out several international spillover scenarios with respect to the United States. First, there are potential supply shocks to the U.S. economy in terms of decreased availability of imported inputs, intermediary goods, and consumption goods. This includes energy and agricultural goods. Second, there could be demand shocks as affected countries decrease their demand for U.S. imports. Third, there may be financial market effects as international willingness to loan to the United States dries up and the value of U.S. firms decline as foreign markets shrink. Fourth, mass migration from heavily affected areas, such as Latin America, will potentially strain the U.S. economy, and likely lead to increased expenditures on migration prevention. Fifth, increases in infectious diseases are likely due to the combined effects of ecological collapse, the breakdown of public infrastructure in poor nations, and declines in the resources available for prevention; increasing mass migration will intensify the spread of diseases across borders. Last, climate change is likely to exacerbate security threats to the United States, partially through its potential destabilizing effect on politics. As a consequence, climate change is a “threat multiplier” in terms of security. In summary, there are a variety of pathways for the effects of climate change in one region to cause damages in another: trade, capital markets, migration, disease, and social conflict.

There are also several potential positive spillover scenarios currently excluded from the SCC. First, trade has the potential to reduce the SCC by reducing the welfare losses to consumers in particularly hard hit regions (Darwin, 1995).¹⁰⁹ While consumers in exporting nations and producers in importing nations are harmed by trade, this loss is more than offset by gains to consumers in importing nations and producers in exporting nations according to economic theory. For example, low elevation nations will experience a decline in domestic agricultural production, but importing food from higher elevation nations will mitigate some of the consumer welfare loss from domestic production declines (Darwin, 1995). Through this lens, trade can be thought of as a form of human adaptation to climate change whereby humans move tradable market goods between the least- and most-affected regions to satisfy the needs of those with the highest demand.¹¹⁰ However, trade can also result in general equilibrium costs, which are also currently omitted (Tol, 2009).¹¹¹ Second, technology spillovers between nations may reduce the regional costs of mitigation and/or adaptation. Investment by developed nations into mitigation and adaptation technologies may reduce the costs of mitigation and adaptation in developing nations (Löschel, 2002; Buonanno et al., 2003; Rao, 2006).¹¹²

The inclusion of inter-regional interactions requires integrating the various regional economic models into an international model. This is technically complex and requires many additional assumptions (Freeman and Guzman, 2009). Care must also be taken to avoid double counting of damages. Rather than simply adding inter-regional damages estimates, modelers have to return to the country-specific damage estimates to examine how they were constructed.

In general, all three IAMs exclude inter-regional damages. There are a few exceptions. First, all three IAMs (DICE-2013, FUND 3.6, and PAGE09) capture general equilibrium effects of trade in the agricultural sector. Second, because GDP measurements include net exports, damage estimates at least partially capture trade indirectly through GDP. Last, FUND models migration as it relates to sea level rise.

FUND 3.6 migration cost estimates are relatively ad hoc and omit several types of damages. First, the method of determining the destination of migrants is ad hoc, and this affects the costs of migration because they are dependent on the destination region.¹¹³ Second, the cost of migration to the sending region is three times its regional per capita income per migrant; Tol (2002) describes three as an “arbitrary” parameter. This approach will underestimate costs of migration if per capita income in coastal regions is greater than the regional average, which would be the case if cities with concentrations of economic activity are affected most by sea level rise. Third, in the region that is receiving migrants, costs per migrant equal 40 percent of per capita income of the receiving country (Cline, 1992 from Fankhauser (1995) from Anthoff and Tol, 2012b); Cline (1992; 120) approximates the costs of migration to the United States based on state and local government infrastructure spending (education, roads, police, sanitation) and taxes paid by immigrants. However, this figure from Cline (1992) was simply an illustration of the cost of migration to the United States and was hardly a “guesstimate,” as stated by Fankhauser. Furthermore, these migration-cost estimates exclude the costs of social conflict from migration pressures (for example, the effect of Syrian migrants on Bulgaria), the potential stress on the receiving country’s social, environmental, and physical infrastructure under cases of mass migration, the psychological cost to migrants of losing their homeland, and the potential physical health costs to refugees (Fankhauser, 1995). Last, FUND sets intra-regional migration costs equal to zero though there is still likely to be stress on the receiving nations (for example, the effect of Syrian migrants on Lebanon and Jordan from the recent Syrian Civil War).¹¹⁶

DESTABILIZERS OF EXISTING NON-CLIMATE STRESSORS. Climate change is often referred to as a threat multiplier. For example, Freeman and Guzman (2009) state that “the consistent message of [national security] studies is that climate change is a ‘threat multiplier’ (Freeman and Guzman, 2009).” While Freeman and Guzman (2009) are mainly referring to national security issues worsening due to climate change further weakening already volatile regions and political unstable nations, their arguments can be generalized to other future challenges that the world faces with or without climate change: social and political instability (Freeman and Guzman, 2009); disease, including the flu (Freeman and Guzman, 2009);¹¹⁷ ecosystem and biodiversity loss (United Nations’ Millennium Ecosystem Assessment);¹¹⁸ decreased water availability.¹¹⁹ In other words, just as the multiple effects of climate change will interact within different economic sectors, as discussed in the previous section under inter-sector damages, non-climate related economic, societal, and environmental pressures will result in multiple damages across sectors due to their interaction with the effects of climate change.

Like inter-sector damages, the interaction of non-climatic factors and the effects of climate change must be captured in the underlying studies utilized to calibrate the IAM damage functions. In most cases, the studies underlying the calibration of the IAMs’ default damage functions do not account for these interactions. Thus, the default versions of the early versions of DICE, DICE-2013, FUND3.6, and PAGE09 by and large omit these damages.

WEATHER VARIABILITY AND CLIMATE EXTREMES. Climate change does not only affect the long-run averages of temperature, precipitation, and sea-level, but also the variability of weather around these changing means. In other words, many more extreme weather events should be expected, including the likelihood of increased: frequency of heat waves, areas experiencing droughts (and some areas experiencing decreased rainfall during monsoons and others experiencing increased aridity), frequency and areas experiencing heavy precipitation events (for example, floods), intensity of tropical cyclones, and extreme high sea level (IPCC, 2007a); see Table 14.

Current IAMs partially capture some of these extremes: tropical storms (hurricanes and typhoons), extra-tropical storms (cyclones), and heat waves. FUND 3.6 explicitly models the economic destruction in terms of lost property and human life (mortality and morbidity) of the increased strength of tropical storms, and the cost to human health (mortality and morbidity) of heat waves, but only to the extent that damages are limited to heat stress. Early versions of DICE, that is, DICE-1999 and DICE-2007, only make an ad hoc account of the loss property, such as human settlements, due to storms in the coastal sector. While both models account for sea-level rise, they fail to account for the interaction between storms and sea level rise, which results in extreme high sea level rise (Yohe and Hope, 2013). As a consequence, the default version of PAGE09 (the damage function of which is greatly informed by FUND and DICE-1999) partially accounts for the cost of the increased intensity of storms and frequency of heat waves. Because most of the underlying studies in DICE-2013 exclude climate extremes, DICE-2013 appears to exclude the economic costs of weather variability (flooding, droughts, and heat waves).

However, these IAMs may implicitly capture some of these extreme events to the extent that these variables are correlated with temperature. Nordhaus (1994a) argues that “in thinking about the impact of climate change we must recognize that the variable focused on in most analyses—globally averaged surface temperature—has little salience for impacts. Rather, variables that accompany or are the result of temperature change—precipitation, water levels, extremes of droughts or freezes, and thresholds like the freezing point or the level of dikes and levees—will drive the socioeconomic impacts. Mean temperature is chosen because it is a useful index of climate change that is highly correlated with or determines the most important variables.” Given that these events are not perfectly correlated with temperature, these events are partially omitted from the analysis. As

Tol (1995) states: “only if the relevant climate parameter relates linearly to the global mean temperature, and the relationship is perfectly known, is the temperature an adequate proxy.” Therefore, these events are already included in the IAMs to the extent that global average surface temperature is correlated with these extreme events. To the extent that they are not, they are excluded.

OCEAN ACIDIFICATION. None of the most widely adopted IAMs for estimating the SCC (DICE, FUND, and PAGE) address the multiple damages due to ocean acidification. As defined by Shinryokan (2011): “Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere.” In terms of market damages, ocean acidification impacts fisheries via its effects on marine ecosystems and organisms, particularly shellfish and crustaceans. In addition to fisheries, ocean acidification will impact ecosystems, biodiversity, and tourism via its effect on coral and also human settlements. While the economic effects of acidification are likely substantial, few economic values of the damages are available because scientists only recently recognized the threat of ocean acidification to marine life (Guinotte and Fabry, 2009) and fisheries, for the most part, are excluded from IAMs; see previous sub-section.

Though fisheries are expected to suffer significant economic damage as a result of ocean acidification, there are few studies of the economic costs of these impacts. Since 2009, economists have completed several impact studies that attempt to more accurately quantify the economic costs of climate change to fisheries. Two such studies, Cooley and Doney (2009) and Narita et al., (2012), estimate these monetary effects with a focus on mollusk production; recent scientific literature finds that acidified ecosystems significantly reduce mollusk populations. Cooley and Doney (2009) conduct a case study of the effect of ocean acidification on U.S. fisheries revenues, with a focus on mollusks. If there were a reduction of 10 percent to 25 percent in the U.S. mollusk harvest from the 2007 level, \$75 million to \$187 million of direct revenue would be lost each subsequent year;¹²⁰ these values correspond to a net present value loss (that is, the sum of annual losses over all futures years in terms of its current dollar value) of \$1.7 billion to \$10 billion through 2060. Similarly, using a partial-equilibrium model to assess the welfare loss to society from a decline in shellfish supply, Narita et al., (2012) find that the costs of ocean acidification could exceed \$100 billion. Because mollusks represent a small fraction of total fisheries, the cumulative economic impact of ocean acidification on fisheries will likely be significantly larger.

In addition to fisheries, ocean acidification will impact tourism associated with the ocean, particularly coral reefs. Coral reefs are expected to be among the worst-affected ecosystems. A study by Brander et al., (2009) considers the economic damages associated with coral reefs and estimates valuation per area. They expect losses in this sector to be at least \$50 billion annually by 2050. It should be noted that the overall effects of climate change on tourism are also excluded, but the magnitude and direction of these effects is uncertain (Tol, 2009; Bigano et al., 2007) and potentially negative (Berrittella et al., 2006).

Adaptation

Some policymakers and analysts may argue that the IAMs need not worry about these omitted damages due to society’s ability to adapt. In other words, adaptation implies that these costs will not be incurred. While adaptation must be accounted for when including the above damage estimates, an altogether elimination of these omitted damages (that is, such that they can be ignored) is unlikely. This is particularly the case for non-market, socially contingent, and catastrophic damages, in general, where adaptation is likely be less effective. This is also increasingly the case for market damages as temperatures increase (Hope, 2011). Furthermore,

adaptation will be particularly difficult for faster-than-expected temperature increases (Anthoff and Tol, 2012; Hope, 2011). The ability to prevent substantial damages through adaptation is limited as evidenced in current IAM damage estimates.

The current IAMs account for adaptation in different ways. In the early versions of DICE and DICE-2013, adaptation is implicit in the damage estimates.¹²¹ As a consequence, the assumptions about adaptation costs are captured in the underlying damage estimates used to calibrate their damage functions (Warren et al., 2006). While Nordhaus implicitly accounts for adaptation to agriculture, other market, health, coastal, and settlement and ecosystem sectors in the early versions of DICE (DICE-1999, DICE-2007, and DICE-2010)—sometimes in an ad hoc way—he essentially assumes high levels of human adaptation at virtually no cost (IWG, 2010). According to IWG (2010) and Warren et al., (2006), this is particularly evident for the other market sectors. It is less clear the extent to which the DICE-2013 damage function captures these adaptation costs due to the use of a meta-analysis. In all versions of DICE, adaptation is not effective enough to eliminate damages.

In FUND, Tol models adaptation explicitly and implicitly. For adaptation to agriculture, ecosystem, and sea level rise damages, Tol models adaptation explicitly. In the first two of these sectors, Tol captures adaptation by modeling damage costs as a function of the rate of climate change (Anthoff and Tol, 2012); see forthcoming Appendix E. In the case of sea level rise, Tol models the cost of building seawalls. Like in DICE, the assumptions about adaptation costs in the other FUND sectors are captured in the underlying damage estimates used to calibrate these damage functions. Additionally, Tol accounts for adaptation implicitly in the energy and human health sectors by allowing regional sector costs to be a function of regional wealth, such that wealthier societies are better able to adapt (IWG, 2010). According to Warren et al., (2006), FUND assumes perfectly efficient adaptation without accounting for adjustment costs, except in the agriculture and ecosystem sectors. Therefore, Tol may underestimate adaptation costs in some sectors of FUND. While climate change results in net global benefits at low temperature changes, higher temperature increases result in costs that adaptation cannot overcome as evidenced by the negative impacts of climate change on consumption by the late 21st century as predicted by FUND 3.6 (Tol, 2013).

Unlike Nordhaus and Tol, Hope (2011) explicitly models climate adaptation in PAGE09. Hope explicitly models adaptation and the cost of adaptation. For each non-catastrophic damage sector (sea level rise, market, and non-market), he specifies a temperature level up to which adaptation is 100 percent effective, a temperature level up to which adaptation is partially effective, and a level of effectiveness (the percentage of damages not incurred) for temperature increases between these two levels. For catastrophic damages, there is no adaptation. Like DICE and FUND, adaptation is not effective enough to significantly eliminate damages.

Given that included damages are significant despite current adaptation assumptions, adaptation as an argument for ignoring currently omitted damages is not justifiable. Furthermore, the three IAMs used by the IWG are often accused of being overly optimistic in their adaptation assumptions, particularly for the versions used by the 2010 IWG (Dietz et al., 2007; Ackerman, 2010; Warren et al., 2006; Hanemann, 2008; Ackerman et al., 2009; Masur and Posner, 2011). In particular, none of the three IAMs explicitly model mal-adaptation. Therefore, omitted damages are likely to still be significant, and current SCC estimates from DICE-2013, FUND 3.6, and PAGE09 are likely biased downward due to a tendency to be overly optimistic about adaptation (Masur and Posner, 2011).¹²²

CONCLUSION — MOVING FORWARD

The IWG SCC estimates are likely biased downward due to the modeling decisions of EPA scientists and IAM developers, including the use of outdated damage estimates and the omission of a significant number of damage categories. While some of the damage estimates utilized by IAMs are outdated (Ackerman, 2010; Stern Review – Chapter 6; Stern, 2007; Dietz et al., 2007; Warren et al., 2006; Warren et al., 2010; Tol, 2009), updating these estimates is likely to have a minimal effect on the SCC (Yohe and Hope, 2013). Instead, this paper focuses on cataloging the more significant damages omitted from the recent versions of the three IAMs used by the Interagency Working Group (DICE-2010, FUND 3.8, and PAGE09), and the latest version of DICE (DICE-2013).¹²³ These omissions occur due to the omission of sectors (for example, socially contingent damages), the omission of relationships between regions and sectors (for example, inter-sector and inter-region damages), and the omission of types of climate damages from the underlying studies used for calibration (for example, fires).

The main question is whether the inclusion of these omitted damages matter. Tol (2009) argues that, for the most part, many omitted damages are small (saltwater intrusion in groundwater, increased cost of cooling power plants, adapting urban water management systems, storm frequency, intensity, and range, ocean acidification, and value of firewood),¹²⁴ and are balanced out by omitted climate benefits (decreased costs of some traditional and alternative energies—oil, wind, and wave, lower transport costs, lower expenditures on food and clothing due to lower demand from higher temperatures, and fewer transportation and other disruptions from cold-related weather).¹²⁵ For others, like tourism, the effects are unknown according to Tol (2009). Instead, Tol (2009) argues that research should primarily focus on estimating and including unknowns that potentially could have large effects, such as biodiversity loss, catastrophic damages, socially contingent damages, and damages at high temperature levels.¹²⁶ In other words, Tol (2009) argues that research should focus on tipping point damages and socially contingent damages; see row 3 and column 3 in Figure 2. Yohe and Tirpak (2007) for the most part agree with this assessment, but also include bounded risks (row 2 in Figure 2), which includes the effects of weather variability (droughts, floods, heat waves, and storms); the effects of weather variability are still greatly omitted from many of the included market and non-market damages. Furthermore, black swan events, that is, unexpected effects, related to climate change should further increase the SCC because researchers expect more negative than positive effects (Tol, 2009b). The inclusion of all omitted damages, including these more significant omitted damages, is likely to result in an increase in the SCC (Mastrandrea, 2009; Tol, 2009a). Given the difficulty of deciding *a priori* what damages are likely to be significant, this report advocates that IAMs should work to include all available damage estimates, particularly those discussed in this paper. However, priority for developing new damage estimates should be given to hot spots—regions and damages that are likely to be significant—for which estimates are not currently available.

There is a general consensus that future IAM research must focus on hot spots. The “hot spot” regions are those that are geographically predisposed to climate change (for example, low lying nations and island nations), and those nations with insufficient ability to adapt (for example, developing nations). The “hot spot” sectors are those discussed above: catastrophic damages, weather variability, and socially-contingent damages. While studying these sectors is difficult, analysts need to look at multiple metrics and regions. The current practice is to omit these difficult to estimate damages or to extrapolate damages estimates from developed to developing nations due to limited data availability. To overcome these shortcomings, future work will require the development of reliable datasets in developing nations and advancements in the science of climate variability and tipping points that specify credible scenarios at a regional level (Yohe and Tirpak, 2007). Furthermore, to develop consistent estimates of damages, the current pipeline of damage estimation, whereby scientists

estimate potential damages and economists draw on these estimates in their studies independent of input from scientists, must be replaced with collaborative research between the disciplines.¹²⁷ This type of research ensures that economists understand the science behind the climate impacts that they are citing, but also ensures that the scientific estimates are developed with the final impact measurement, that is, the dollar impact, in mind.

Alternatively, further attempts to utilize meta-analysis at the aggregate scale (across regions and sectors) as is done in DICE-2013 are ill-advised.¹²⁸ There are several reasons to advise against this type of damage-function estimation. First, using meta-analysis makes determining which damages are included and excluded difficult. It requires an analyst to thoroughly study each of the underlying studies to determine which climate impacts on a sector are included and excluded. Furthermore, it is difficult to interpret whether an impact is included if only several studies include the impact. Second, there are too few data points at this scale to properly account for statistical issues: time trends, omitted damage sectors or impacts within sectors, and correlated standard errors between studies that include estimates from the same authors and similar estimation methods. Last, as discussed by Tol (2009), the data points from various studies are not really a time-series, and should not be treated as such. An alternative is to conduct meta-analyses at the sector level where a sufficient number of studies are available. For example, there are a multitude of agricultural studies, and a meta-analysis to estimate a regional-agricultural or global-agricultural damage function would be possible. Another alternative, laid out by Kopp, Hsiang, and Oppenheimer (2013) is to develop an infrastructure that uses statistical (for example, Bayesian) methods to update damage functions as new estimates become available.

Though not discussed in this paper, there are several additional compounding aspects of IAMs that are likely to further bias current SCC estimates downward. In particular, they fail to account for (1) uncertainty in extrapolating damages to higher temperatures given that IAMS assume only moderate temperature increases,¹²⁹ (2) a declining discount rate due to uncertainty over future economic growth (Arrow et al., 2013),¹³⁰ (3) aggregated and overly simplified spatial and temporal resolution (IWG 2010; Hanemann, 2008; Stern, 2007), and (4) the option value that arises from the irreversibility of CO₂ emissions. These shortcomings, by and large, point to a further bias downward of the social cost of carbon.

While there is a downward bias to the federal SCC estimates, this report advocates that the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates, as measuring at least some of the costs is better than assuming there are none. In doing so, the OMB should emphasize more strongly the downward bias of the current U.S. SCC estimates and commit to addressing them in future updates of these estimates. Potentially, OMB can utilize the research provided in this report to list in detail all of the omitted damages in the current U.S. SCC estimates.

Table 1. 2010 and 2013 SCC Estimates at 3% Discount Rate by Model

IAM	2010 Global SCC at 3% Discount Rate (IWG 2010)	2020 Global SCC at 3% Discount Rate (IWG 2013)	% Change
DICE	\$28	\$38	34%
FUND	\$6	\$19	222%
PAGE	\$30	\$73	143%

Source: IWG (2013 Revision)

Table 2. 2010 SCC Estimates, 2010–2050 (in 2007 dollars per metric ton)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Source: IWG (2010)

Table 3. 2013 SCC Estimates, 2010–2050 (in 2007 dollars per metric ton)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	11	32	51	89
2015	11	37	57	109
2020	12	43	64	128
2025	14	47	69	143
2030	16	52	75	159
2035	19	56	80	175
2040	21	61	86	191
2045	24	66	92	206
2050	26	71	97	220

Source: IWG (2010)

Table 4. Damage Studies and Income Elasticities Used to Estimate DICE-1999 Damage Function

Sector	Source of Damage Estimate (2.5 degrees Celsius)	Notes	Income Elasticity
Agriculture	Darwin et al (1995) and Dinar et al (1998)	Sub-regional impact estimates: Darwin et al (1995) and Dinar et al (1998); mainly uses Appendix Table B6 from Darwin et al (1995) assuming second most unfavorable GCM and land use is unrestricted.	0.1
Other Market Sectors	Author discretion	Unknown sources for sub-regional damage estimates. No damages to temperate climates based on Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999). Damages in non-temperature climates (cold, tropical, and semi-tropical) based on energy sector alone.	0.2
Coastal Vulnerability	Author discretion	Not directly based on one specific study, but highly influenced by Yohe and Schlesinger (1998); study omits storms, undeveloped land, and settlement so accounted for by author discretion.	0.2
Health	Murray and Lopez (1996)	Assign regional impacts based on the region from Murray and Lopez (1996) with which it most overlaps.	0
Non-market Impacts	Nordhaus (1998)	Use the Nordhaus (1998) estimate from climate-related time use in the U.S.; focusing mainly on increased outdoor recreation.	0
Human Settlement and ecosystems	Author discretion	Cite their own unpublished estimates of the capital value of climate sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system for a 2.5 degrees increase.	0.1
Catastrophic Climate Change*	Nordhaus (1994)	Assume 30% loss of global GDP for such an event and a rate of relative risk aversion of 4 for catastrophic risk. They use expert opinions of probabilities of a cataclysmic change drawn from Nordhaus (1994); the authors double the probabilities in the study for increasing concerns about these events for both 2.5 (measured at 3 degrees in study) and 6 degrees.	0.1

*Calibration sources are provided for 2.5 degrees of warming, but not 6 degrees of warming. The one exception is catastrophic events.

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

Table 5. Sector-Region Specific Damage Estimates for DICE-1999

Subregion	Non-catastrophic impacts						Catastrophic impact				TOTAL	
	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use*	Settlements and ecosystems*	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius
Africa	0.05%	0.09%	0.02%	3.00%	0.25%	0.10%	0.39%	2.68%	0.39%	2.68%	3.91%	-
China	-0.37%	0.13%	0.07%	0.09%	-0.26%	0.05%	0.52%	3.51%	0.52%	3.51%	0.22%	-
Eastern Europe	0.46%	0.00%	0.01%	0.02%	-0.36%	0.10%	0.47%	3.23%	0.47%	3.23%	0.71%	-
High Income OPEC	0.00%	0.91%	0.06%	0.23%	0.24%	0.05%	0.46%	3.14%	0.46%	3.14%	1.95%	-
India	1.08%	0.40%	0.09%	0.69%	0.30%	0.10%	2.27%	15.41%	2.27%	15.41%	4.93%	-
Japan	-0.46%	0.00%	0.56%	0.02%	-0.31%	0.25%	0.45%	3.04%	0.45%	3.04%	0.50%	-
Low Income	0.04%	0.46%	0.09%	0.66%	0.20%	0.10%	1.09%	7.44%	1.09%	7.44%	2.64%	-
Lower-middle Income	0.04%	0.29%	0.09%	0.32%	-0.04%	0.10%	1.01%	6.86%	1.01%	6.86%	1.81%	-
Middle Income	1.13%	0.41%	0.04%	0.32%	-0.04%	0.10%	0.47%	3.21%	0.47%	3.21%	2.44%	-
OECD Europe	0.49%	0.00%	0.60%	0.02%	-0.43%	0.25%	1.91%	13.00%	1.91%	13.00%	2.83%	-
Other High Income	-0.95%	-0.31%	0.16%	0.02%	-0.35%	0.10%	0.94%	6.39%	0.94%	6.39%	-0.39%	-
Russia	-0.69%	-0.37%	0.09%	0.02%	-0.75%	0.05%	0.99%	6.74%	0.99%	6.74%	-0.65%	-
United States	0.06%	0.00%	0.11%	0.02%	-0.28%	0.10%	0.44%	2.97%	0.44%	2.97%	0.45%	-
Global: 2100 GDP weights (i.e., 2.5 degrees Celsius)												
Output-weighted	0.13%	0.05%	0.32%	0.10%	-0.29%	0.17%	1.02%	6.94%	1.02%	6.94%	1.50%	8.23%

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

Table 6. Sector-Region Specific Damage Estimates for DICE-2007

Non-catastrophic impacts										Catastrophic impact				TOTAL	
	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use*	Settlements and ecosystems*	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius	6 degrees Celsius
United States	0.03%	0.00%	0.10%	0.02%	-0.28%	0.10%	0.94%	4.00%	0.91%	4.00%	0.91%	4.00%	0.91%	4.00%	5.34%
European Union	0.03%	0.00%	0.46%	0.02%	-0.43%	0.25%	1.09%	4.80%	1.42%	4.80%	1.42%	4.80%	1.42%	4.80%	9.06%
Add'l High Income	-0.05%	-0.32%	0.09%	0.02%	-0.35%	0.10%	1.11%	4.80%	0.61%	4.80%	0.61%	4.80%	0.61%	4.80%	8.99%
Russia	-0.82%	-0.80%	0.05%	0.02%	-0.75%	0.05%	1.12%	4.80%	-1.13%	4.80%	-1.13%	4.80%	-1.13%	4.80%	8.43%
Eurasia	0.03%	0.00%	0.01%	0.02%	-0.36%	0.10%	0.94%	4.00%	0.73%	4.00%	0.73%	4.00%	0.73%	4.00%	4.76%
Japan	0.02%	0.00%	0.27%	0.02%	-0.31%	0.25%	1.07%	4.80%	1.31%	4.80%	1.31%	4.80%	1.31%	4.80%	8.84%
China	0.02%	0.32%	0.08%	0.09%	-0.26%	0.05%	1.04%	4.00%	1.34%	4.00%	1.34%	4.00%	1.34%	4.00%	7.92%
India	0.32%	0.29%	0.09%	0.40%	0.30%	0.10%	1.57%	6.00%	3.08%	6.00%	3.08%	6.00%	3.08%	6.00%	12.94%
Middle East	0.35%	0.20%	0.04%	0.23%	0.24%	0.05%	0.96%	4.00%	2.08%	4.00%	2.08%	4.00%	2.08%	4.00%	8.41%
Africa	0.67%	0.32%	0.02%	1.00%	0.25%	0.10%	1.78%	7.00%	4.13%	7.00%	4.13%	7.00%	4.13%	7.00%	16.55%
Latin America	0.42%	0.28%	0.10%	0.32%	-0.04%	0.10%	1.30%	5.20%	2.48%	5.20%	2.48%	5.20%	2.48%	5.20%	10.36%
Other Asia	0.52%	0.21%	0.09%	0.32%	-0.04%	0.10%	1.23%	5.00%	2.43%	5.00%	2.43%	5.00%	2.43%	5.00%	10.00%
Global: 2105 weights (i.e. 2.5 degrees Celsius)															
Output weighted	-	-	-	-	-	-	1.16%	4.72%	1.77%	4.72%	1.77%	4.72%	1.77%	4.72%	8.23%

Source: Nordhaus (2007)

Table 7. Damage Studies Used to Estimate the DICE-2013 Damage Function

Study	Temperature	Damage Estimate
Tol (2002)	1	-2.875
Rehdanz and Maddison (2005)	1	0.5
Hope (2006)	2.5	-1.125
Mendelsohn, Schlesinger, and Williams (2000)	2.5	0
Maddison (2003)	2.5	0.125
Nordhaus (2006)	2.5	1.125
Fankhauser (1995)	2.5	1.75
Nordhaus and Boyer (2000)	2.5	1.875
Nordhaus and Yang (1996)	2.5	2.125
Tol (1995)	2.5	2.375
Plambeck and Hope (1996)	2.5	3.125
Nordhaus (1994a)	3	1.625
Nordhaus (1994b)	3	6

Source: Tol (2009)

Table 8. PAGE 2002 Damage Function Parameters and Data Sources

Damage parameter	Mean	Min	Mode	Max	Source
Market Damages					
Econ impact in EU (%GDP for 2.5°C)	0.5	-0.1	0.6	1	IPCC (2001a, pp. 940, 943.)
Drop in econ impact OECD (%)	90				As in PAGE95a
Drop in econ impact RoW (%)	50				As in PAGE95a
Tolerable temp OECD economic (°C)	2				As in PAGE95a
Non-Market Damages					
Non-economic impact in EU (%GDP for 2.5°C)	0.73	0	0.7	1.5	IPCC (2001a, pp. 940, 943.)
Drop in non-econ impact (%)	25				As in PAGE95a
Market and Non-market					
Impact function exponent	1.76	1	1.3	3	As in PAGE95
Eastern Europe & FSU weights factor	-0.35	-1	-0.25	0.2	IPCC (2001a, p. 940.)
USA weights factor	0.25	0	0.25	0.5	IPCC (2001a, p. 940.)
China weights factor	0.2	0	0.1	0.5	IPCC (2001a, p. 940.)
India weights factor	2.5	1.5	2	4	IPCC (2001a, p. 940.)
Africa weights factor	1.83	1	1.5	3	IPCC (2001a, p. 940.)
Latin America weights factor	1.83	1	1.5	3	IPCC (2001a, p. 940.)
Other OECD weights factor	0.25	0	0.25	0.5	IPCC (2001a, p. 940.)
Tipping Point Damages					
Tolerable before discontinuity (°C)	5	2	5	8	IPCC (2001a, p. 952.)
Chance of discontinuity (% per °C)	10.33	1	10	20	
Loss if discontinuity occurs, EU (%GDP)	11.66	5	10	20	IPCC (2001a, p. 947.)

Source: Hope (2006)

Table 9. PAGE 2009 Damage Function Parameters and Data Sources

Damage parameter	Mean	Min	Mode	Max	Source
Sea Level Rise					
Initial Benefit (%GDP/°C)	0	0	0	0	-
Calibration sea level rise (m)	0.5	0.45	0.5	0.55	Anthoff et al., 2006
Sea level impact (% GDP)	1	0.5	1	1.5	Warren et al., 2006*
Sea level exponent	0.73	0.5	0.7	1	Anthoff et al., 2006
Market Damages					
Economic Initial benefits (%GDP/°C)	0.13	0	0.1	0.3	Tol, 2002
Econ impact in EU (%GDP for Cal. Temp.)	0.5	0.2	0.5	0.8	Warren et al., 2006*; IPCC AR4
Economic exponent	2.17	1.5	2	3	Ackerman et al, 2009
Non-Market Damages					
Non-economic Initial benefits (%GDP/°C)	0.08	0	0.05	0.2	Tol, 2002
Impact in EU (%GDP for Cal. Temp.)	0.53	0.1	0.5	1	Warren et al., 2006*; IPCC AR4
Non-economic exponent	2.17	1.5	2	3	Ackerman et al, 2009
Market and Non-market					
Calibration temperature (°C)	3	2.5	3	3.5	Warren et al., 2006*
Sea Level Rise, Market, and Non-market					
Impacts saturate beyond (% consumption)	33.33	20	30	50	Weitzman, 2009
US weights factor	0.8	0.6	0.8	1	Anthoff et al, 2006; Stern 2007, p143.**
OT weights factor	0.8	0.4	0.8	1.2	
EE weights factor	0.4	0.2	0.4	0.6	
CA weights factor	0.8	0.4	0.8	1.2	
IA weights factor	0.8	0.4	0.8	1.2	
AF weights factor	0.6	0.4	0.6	0.8	
LA weights factor	0.6	0.4	0.6	0.8	

Damage parameter	Mean	Min	Mode	Max	Source
Tipping Point Damages					
Tolerable before discontinuity (°C)	3	2	3	4	Lenton et al, 2008, table 1; Stern, 2007, box 1.4
Chance of discontinuity (% per °C)	20	10	20	30	Ackerman et al, 2009; Lenton et al, 2008, table 1; Stern, 2007, box 1.4
Loss if discontinuity occurs, EU (%GDP)	15	5	15	25	Anthoff et al, 2006 is the lower number; middle range is Nicholls et al, 2008, and the upper figure is Nordhaus, 1994.
Half-life of discontinuity	90	20	50	200	Hansen (2007) for short values; medium and long-run effects from Nicholls et al. (2008) and Lenton et al. (2008)

* Hope (2011) states that “They produce a mean impact before adaptation of just under 2% of GDP for a temperature rise of 3 °C (Warren et al, 2006), including the associated sea level rise of just under half a meter (Anthoff et al, 2006).”

Table 10. Taxonomy of Omitted Damages – Used in This Paper

Damage Category	Missing Damage Sector
Market Damages	Fisheries
	Pests, pathogens, and weeds
	Erosion
	Fire
	Energy Supply
	Transportation
	Communication
	Ecological dynamics
	Decreasing growth rate
Non-Market Damages	Recreational goods and services
	Ecosystem services*
	Biodiversity and habitat*
	Health care costs*
	Relative prices
Socially-Contingent Damages	Migration
	Social and political conflict
	Violence and crime
Catastrophic Damages	Tipping point*
	Fat tails
	Black swan events
Inter-Sector Damages	Inter-sector damages
Cross-Sector Damages	Inter-regional damages
	Destabilizers of existing non-climate stressors
	Weather variability and climate extremes
	Ocean acidification.

*Partially and/or insufficiently captured in current versions of DICE, FUND, and PAGE

Table 11. Alternative taxonomy of Omitted Damages

Damage Category	Damage sub-category	Missing Damage Sector
Missing Sector	Missing market and non-market sectors	Fisheries
		Energy Supply
		Transportation
		Communication
		Recreational goods and services
	Missing interactions	Inter-sector damages
		Inter-regional damages
	Poorly/incompletely estimated sectors	Biodiversity and habitat*
		Ecosystem services*
		Health care costs*
Missing Climate Effects	Broad system changes	Tipping point*
		Fat tails
		Black swan events
		Weather variability and climate extremes
		Ocean acidification
	Specific impacts from broad system changes	Ecological dynamics
		Pests, pathogens, and weeds
		Erosion
		Fire
	Missing dynamic climate effects	Decreasing growth rate
		Relative prices
		Socially contingent damage

*Partially and/or insufficiently captured in current versions of DICE, FUND, and PAGE

Table 12. Percentage Difference in Damages (with respect to European Damages) by Region and IAM (%)

	PAGE02	Mendelson et al (2000)	Nordhaus and Boyer (2000)	Tol (1999)	Tol's SE	Tol's Lower 95%	Tol's Upper 95%
US	25	-	17.86	91.89	-	-171.24	71.79
Europe	100	-	100	100	-	100	100
Japan/ Other OECD	25	-	17.86	27.03	-	188.89	39.39
Eastern Europe	-35	-	25 and -25	54.05	-	890.20	117.92
Middle East	-	-	-	29.73	-	524.84	67.55
Latin America	183	-	71.43	-2.70	-	208.50	13.43
South East Asia/India	250	-	175	-45.95	-	630.07	5.69
China	20	-	7.14	56.76	-	1258.17	148.53
Africa	183	-	139.29	-110.81	-	1374.51	2.65

Source: IPCC (2001)

Table 13. Damages by Region (as a % of GDP) and IAM

	PAGE02	Mendelson et al (2000)	Nordhaus and Boyer (2000)	Tol (1999)	Tol's Lower 95%	Tol's Upper 95%
US	-0.32	0.3	-0.5	3.4	1.048	5.752
Europe	-1.28	-	-2.8	3.7	-0.612	8.012
Japan/ Other OECD	-0.32	-0.1	-0.5	1	-1.156	3.156
Eastern Europe and Russia (FSU)	0.448	11.1	-0.7 and 0.7	2	-5.448	9.448
Middle East	0	-	0.7	1.1	-3.212	5.412
Latin America/Brazil	-2.3424	-1.4	-2	-0.1	-1.276	1.076
South East Asia/India	-3.2	-2	-4.9	-1.7	-3.856	0.456
China	-0.256	1.8	-0.2	2.1	-7.7	11.9
Africa	-2.3424	-	-3.9	-4.1	-8.412	0.212

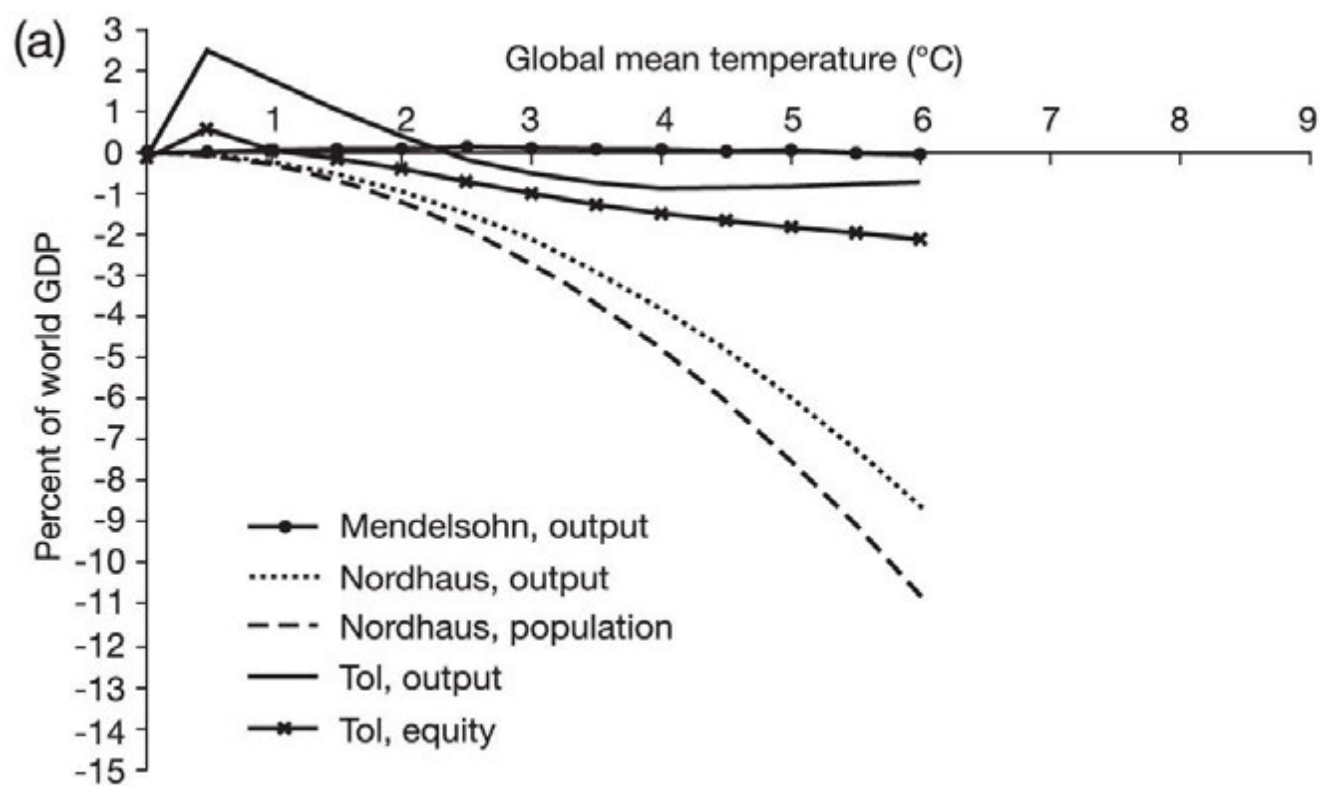
Source: IPCC (2001)

Table 14. Extreme Events

Phenomenon and direction of trend	Likelihood that trend occurred in late 20th century (typically post 1960)	Likelihood of a human contribution to observed trend	Likelihood of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	Very likely	Likely	Virtually certain
Warmer and more frequent hot days and nights over most land areas	Very likely	Likely (nights)	Virtually certain
Warm spells/heat waves. Frequency increases over most land areas	Likely	More likely than not	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	More likely than not	Very likely
Area affected by droughts increases	Likely in many regions since 1970s	More likely than not	Likely
Intense tropical cyclone activity increases	Likely in some regions since 1970	More likely than not	Likely
Increased incidence of extreme high sea level (excludes tsunamis)	Likely	More likely than not	Likely

Source: IPCC (2007a) – Summary for Policymakers, Table SPM.2 on page 8

Figure 1. Damage Estimates as a % of Global GDP vs. Global Mean Temperature



Source: Figure 20.3a in IPCC (2007) and Figure 19.4 in IPCC (2001b)

Figure 2. Map of types of damages in IAMS by level of scientific and economic uncertainty

UNCERTAINTY IN VALUATION →				
UNCERTAINTY IN PREDICTING CLIMATE CHANGE ↓		MARKET	NON MARKET	(SOCIAL CONTINGENT)
	PROJECTION (e.g. sea level rise)	I Coastal projection Loss of dryland Energy (heating/cooling)	IV Heat stress Loss of wetland	VII Regional costs Investment
	BOUNDED RISKS (e.g. droughts, floods, storms)	II Agriculture Water Variability (drought, flood, storms)	V Ecosystem change Biodiversity Loss of life Secondary social effects	VIII Comparative advantage & market structures
	SYSTEM CHANGE & SURPRISES (e.g. major events)	III Above, plus Significant loss of land and resources Non-marginal effects	VI Higher order Social effects Regional collapse	IX Regional collapse

Source: Yohe and Tirpak (2007)

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- ¹ In other words, the SCC is the marginal cost of carbon as measured by the present value of all future damages.
- ² This integration is necessary to capture the various steps of the climate process that translate an additional unit of carbon into a social welfare loss: economic and population growth emissions atmosphere concentrations temperature changes economic damages welfare loss.
- ³ FUND 3.5 and FUND 3.8 were released in 2009 and 2012, respectively. At the time that this report was written, documentation for FUND was only available up until version 3.6. Since then, Tol released the documentation for version 3.7. Only small changes were made between versions 3.7 and 3.8 based upon peer reviewed science updates.
- ⁴ The IWG provides four SCC estimates. Averaging SCC estimates across all IAMs and socio-economic scenarios (giving each equal weight), the updated estimates for the 2015 social cost of carbon are \$11, \$37, and \$57 for discount rates of 5 percent, 3 percent, and 2.5 percent, respectively, and \$109 for the 95th percentile SCC at a 3 percent discount rate averaged across all IAMs and scenarios.
- ⁵ This includes maintaining assumptions about the climate sensitivity parameter, socio-economic and emissions scenarios, and discount rates used in 2010 estimates.
- ⁶ While continued effort is necessary to update damage estimates currently included in IAMs, which often date back to the 1990s (Ackerman 2010; Dietz et al., 2007; Warren et al., 2006; Tol 2009), Yohe & Hope (2013) demonstrates, within the context of the PAGE model, that updates to market damage estimates (equivalent to a 10 percent increase or decrease) will only slightly affect the SCC. Instead, Yohe & Hope (2013) highlight non-economic (also known as non-market) damages, some of which are omitted from IAMs, as areas for more effective improvement (Yohe & Tirpak 2008). In other words, significant downward bias is more likely to result from omitted damages than from outdated damages.
- ⁷ The three models we discuss in this report are not those used by the 2013 IWG. Similar to the 2013 IWG, we discuss PAGE09. Unlike the 2013 IWG, we also discuss DICE-2013 and FUND 3.6. The 2013 IWG utilized DICE-2010 in their calculations instead of DICE-2013. However, because DICE-1999 is utilized in the calibration of PAGE09 and the damage function in DICE-2010 is very similar to the damage function in DICE-1999, we implicitly discuss the omitted damages in DICE-2010. The 2013 IWG utilized FUND 3.8 in their calculations instead of FUND 3.6. However, at the time this report was researched, documentation for FUND was only available up until FUND 3.6. Tol only made minor changes between versions 3.6 and 3.8. For the purposes of this report, no additional damages were included by the author.
- ⁸ Market damage estimates are generally based on either an enumerative approach or a statistical approach. The enumerative approach takes estimates of the physical impacts of climate change by sector (e.g., impact on crop yield or land lost through sea level rise) and then applies economic indicators (e.g., market crop prices or coastal land values) to estimate damages. Specifically, analysts combine physical impact studies from the sciences with prices from economic studies to determine damage estimates, and then, because many of these damage studies are region and sector (e.g., agriculture, forestry, etc.) specific in nature, utilize benefit transfer and aggregation methods to produce a global damage estimate. The statistical approach estimates welfare changes by observing variations in prices and expenditures across space under varying climate conditions. Specifically, analysts estimate climate damages using econometric techniques based on current observations of the climate and economic variables (income, budget shares, and happiness measurements). Enumerative studies have been criticized for ignoring overlaps and interactions between sectors. Statistical surveys draw criticism for overlooking important, non-climate regional differentiators such as structural institutions and for excluding damages that vary temporally but not spatially (i.e., sea level rise and catastrophic impacts). In other words, both estimation methods rely heavily on extrapolation (Goulder & Pizer, 2006; Tol, 2009; Brouwer & Spaninks, 1999).
- ⁹ For example, in the United States, climate-related increases in morbidity and mortality comprise 6 percent to 9 percent of the decrease in GDP but 13 percent to 16 percent of the decrease in household welfare (Jorgenson et al., 2004).
- ¹⁰ While the transition point from climate benefits to climate damages in Tol (2009) is incorrect in magnitude due to a sign error in the citation of the damage estimate from PAGE02 (Hope 2006) and several other citation errors, the general result of positive net benefits from climate change will likely still hold for low temperature increases after their correction. However, the transition point is likely to occur at a lower temperature threshold.

- ¹¹ While Nordhaus assumes no initial benefits from climate change in DICE-2007 and DICE-2013, he allows for initial benefits in DICE-1999 and DICE-2010; Nordhaus estimates net global benefits from climate change up until a 1.29°C increase in global surface temperature in DICE-1999, and no initial benefits in DICE-2010. Hope explicitly models initial benefits in PAGE09, but does not in PAGE02; only Eastern Europe and the former Soviet Union experience climate benefits in PAGE02, which is captured implicitly through a negative damage weighting factor. In PAGE09, Hope includes an additional term in the market and non-market damage functions to account for climate benefits for low temperature increases above pre-industrial levels. This allows for the possibility of positive benefits from climate change, though the exact threshold depends on the parameters drawn; see discussion below. In FUND 2.0, Tol (2002a) finds a net global benefit from climate change equivalent to 2.3 percent of GDP for a one degree Celsius increase; the resulting threshold is less clear.
- ¹² Because prices are not directly associated with non-market goods as they are with market commodities, a range of alternative valuation methodologies estimating preferences can be used. The value methodologies are traditionally grouped into revealed and stated preference techniques. Revealed preference techniques use market goods to estimate the value of environmental or safety amenities embedded in their prices (e.g., property value variations as a function of parks or pollution levels associated with different homes). In other words, these revealed preference methodologies assume that the price of market goods (e.g., property values) reflect the value of the ecological services or that, *ceteris paribus*, people will pay more to travel to places with greater ecological value. The usefulness of revealed preference methods in assessing non-market damages is limited because most non-market impacts do not induce price or quantity changes; this is particularly true for the valuation of species, habitat, and ecosystem services. Stated preference methods use interviews or surveys asking participants to identify either the price they would pay for a given ecological commodity, or the amount of a non-market commodity they would demand at a given monetary amount. While stated preference methods can be utilized to assess the willingness to pay (WTP) for non-market goods (Tol 2009; Smith et al., 2003), they have other limitations. In particular, answers depend on question wording, ordering effects, and practical or cognitive limitations in putting dollar values on intangible goods. They may also suffer from information limitations, depending on the good being valued.
- With respect to environmental non-market goods, Boyd & Krupnick (2009) and others have compared ecological and economic production systems, arguing that valuation of ecosystem services implies a valuation of their respective outputs. These “outputs” (e.g., reduced flood risk, flourishing fish populations) can be reliably understood and valued by the public in ways that specific ecosystem services (e.g., nutrient cycling) cannot. Because an individual values the endpoint and not the process itself, when asked to value a specific ecosystem service, an individual will base his WTP for the service on his WTP for the “output” of that service. Stated preference valuation that focuses on the value of specific services (instead of outputs) often prove inaccurate because those surveyed assume ecological production factors that may not be consistent with each other or with reality (Boyd & Krupnick 2009).
- ¹³ In other words, tipping points are generally more common in systems with intricate, codependent processes that when altered by exogenous conditions result in the failure of beneficial negative feedback loops or the propagation of detrimental positive feedback loops.
- ¹⁴ Using a similar set of tipping elements, Nordhaus (2013) identifies four global tipping points: (1) collapse of large ice sheets, (2) large-scale change in ocean circulation, (3) feedback processes that trigger more warming, and (4) enhanced warming over the long-run.
- ¹⁵ Anthoff and Tol (2013a) claim that FUND implicitly captures catastrophic damages. Specifically, catastrophic impacts arise by modeling the uncertainty of 900 parameters in the FUND model.
- ¹⁶ More formally, Weitzman (2009) defines a probability distribution function as having fat tails “when its moment generating function (MGF) is infinite—that is, the tail probability approaches 0 more slowly than exponentially.” Conversely, he defines a thin-tailed distribution as one characterized by “a [probability distribution function] whose [moment generating function] is finite.” Nordhaus (2012) defines a fat-tail distribution as a distribution that follows a power law, which is a “distribution in which the probability is proportional to a value to a power or an exponent.”
- ¹⁷ For clarification purposes, medium-tailed distributions are sometimes referred to as thin-tailed distributions. This paper follows the convention laid out in Nordhaus (2012).
- ¹⁸ Weitzman (2011) states that the “recipe” for fat tails is “deep structural uncertainty about the unknown unknowns of what might go very wrong ... coupled with essentially unlimited downside liability on possible planetary damages.” In other words “the operation of taking ‘expectations of expectations’ or ‘probability distributions of probability distributions’ spreads apart and fattens the tails of the reduced-form compounded posterior-predictive PDF (Weitzman 2009).”

- ¹⁹ Weitzman argues that existing IAMs underestimate the decrease in welfare-equivalent output for extremely high changes in global temperature. The DICE-2010 model, for example, predicts that a 10°C increase in the mean global temperature would result in a 19 percent loss in global welfare equivalent output. Weitzman contends that for very large increases in global temperature damage functions lose much of their predictive ability as complications in spatial and temporal averaging as well as a priori conjecture compound (Weitzman 2011). This implies that there is considerable uncertainty over climate damages at high temperature levels.
- ²⁰ Using the value of civilization, Weitzman (2009) calculates a lower bound on consumption (i.e., survival level of consumption), and demonstrates that it is decreasing in the value of civilization.
- ²¹ Citing Yohe & Tirpak (2008) and Tol (2008), Mastrandrea (2009) states that “while there certainly may be unassessed positive impacts from climate change, such summaries suggest that they are likely to be outweighed by unassessed negative impacts.”
- ²² The choice of functional form determines how climate damages are projected to higher temperatures and does not determine which damages are accounted for and which are omitted.
- ²³ IAM damage functions are usually calibrated with one point estimate (i.e., at one temperature level), though DICE-1999 is calibrated with two point estimates (i.e., at two temperature levels). In both cases, the lack of damage estimates from climate change at high temperatures makes results unreliable at high temperature (Kopp & Mignone 2012). On the one hand, if analysts use a point estimate (i.e., damage estimates at a particular temperature increase) to calibrate damage functions, the functional form determines damages at high future temperatures. However, without estimates at higher temperatures, analysts cannot determine the correct functional form (Kopp & Mignone 2012). On the other hand, if analysts use multiple point estimates, analysts must extrapolate low temperature damage estimates to high temperatures; this requires a multitude of assumptions, as in DICE-1999, making damage estimates at high temperature unreliable. There are several alternatives. One alternative, utilized by Ackerman & Stanton (2012), is to assume that climate damages reach 100 percent of GDP at a particular temperature level based on the Weitzman argument that humans cannot live at 12 degrees Celsius higher. Another alternative, utilized by Hope (2006; 2011), is to conduct sensitivity analysis over the calibration temperature and damage value.
- ²⁴ FUND calibrates sector damage functions to a one degree Celsius increase in temperature. Unlike DICE and PAGE, which assume that climate damages are power functions of temperature increases, Tol assumes sector-specific equations of motion (equations that specify how damages evolve over time based on how physical systems, emissions, income, and population underlying these damages change over time) to extrapolate damage estimates to higher temperatures (and time periods). These equations rely on various assumptions about physical and economic processes, and rely heavily on parameter calibration.
- ²⁵ In terms of author discretion, all three IAMs rely heavily on author discretion. However, this reliance has declined with newer versions of the models.
- ²⁶ In addition to the default versions of these IAMs, various other versions of these models exist in publication where analysts (including the original developers) modify the default versions to capture differing growth paths or other potential variations.
- ²⁷ Whether the damage functions have a linear term, which allows for initial benefits from climate change, in addition to the quadratic term, depends on the version of the model. Only DICE-1999 and DICE-2010 include these linear terms, while Nordhaus sets this parameter equal to zero in DICE-2007 and DICE-2013.
- ²⁸ The regions in the DICE-1999 model are: United States, China, Japan, OECD Europe, Russia, India, other high income, high-income OPEC, Eastern Europe, middle income, lower middle income, Africa, and low income.
- ²⁹ Because the DICE-1999 climate damages are a function of temperature and temperature squared, two data points are necessary to calibrate the damage equation: damage estimates at 2.5 degrees and 6 degrees Celsius. Damage estimates for a 2.5 degree Celsius increase are available in the literature. Due to unavailability of damage estimates at 6 degrees, damage estimates at 2.5 degrees Celsius are extrapolated to 6 degrees Celsius.
- ³⁰ Nordhaus makes several updates to the damage estimates because some regions had climate benefits for high temperatures and catastrophic damages could have been calibrated more carefully in DICE-2000. First, Nordhaus calibrates the damage function using agricultural damage estimates drawn from “Cline’s agricultural studies.” However, it is unclear which of Cline’s papers were used. Second, he no longer accounts for risk aversion when calculating catastrophic damages. This adjustment lowers catastrophic damage estimates. Third, Nordhaus utilizes updated regional GDP estimates to aggregate regional damage estimates to the global scale. In addition, Nordhaus drops the linear term from the quadratic

damage function (Nordhaus, 2008). Fourth, though not mentioned in Nordhaus (2008), Nordhaus does not extrapolate damages from low levels to high levels as discussed in Nordhaus and Boyer (2000); this is possible because Nordhaus eliminates the linear temperature term in the damage function. Last, Nordhaus changes the regions in the model to: the United States, Western Europe/European Economic Zone, Other-High Income, Russia, Eastern Europe/Former Soviet Union, Japan, China, India, Middle Eastern, Sub-Saharan Africa, Latin America, and Other Asian. See Table 6 for DICE-2007 region-sector specific damage estimates.

- ³¹ Anthoff and Tol (2013a) states that “FUND does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realizations are catastrophic.”
- ³² Again, this discussion refers to the default version of PAGE09.
- ³³ According to Hope (2006), in PAGE02, the economic and non-economic damage estimates for 2.5 degree Celsius increase in temperature is based on pages 940 and 943 of the IPCC (2001a) and the tipping point damages are based on pages 947 and 952 of the IPCC (2001a). The combined market and non-market damage estimates on page 940, i.e., Table 19-4, include Pearce et al. (1996), Tol (1999), Mendelsohn et al., (2000), and Nordhaus and Boyer (2000), and the estimates on page 943, i.e., Figure 19-4, include Tol (2002a), Mendelsohn & Schlesinger (1997), and Nordhaus & Boyer (2000). Because the IPCC (2001a) cites only global damage estimates for Pearce et al., (1996) in Table 19-4 and it does not include estimates for Pearce et al., (1996) in Figure 19-4, it is likely that Hope (2006) does not base his regional damage estimates on this source. Similarly, because the IPCC (2001a) does not cite European climate damage estimates for Mendelsohn et al., (2000) in Table 19-4 and cites different estimates from Mendelsohn, i.e., Mendelsohn & Schlesinger (1997), in Figure 19-4, it is again likely that Hope (2006) does not base his damages estimates on this source. Furthermore, the damage estimate of a 1.23 percent decline in GDP (with a range of -0.1 percent to 2.5 percent) used in PAGE2002 for Europe for a 2.5 degree Celsius increase in temperature do not match the damage estimates from Tol (1999) of a 3.7 percent increase in GDP for Europe with a standard deviation of 2.2 percent and a -2.8 percent decline in European GDP from a 2.5 degree Celsius increase in temperature; see Tables 10 and 11. Instead the damage estimates are closer to the Nordhaus & Boyer (2000) damage estimates. However, the Hope (2006) damage estimates do not replace Nordhaus & Boyer (2000). Similarly, it is unclear what source Hope (2006) uses to breakdown damage estimates between his market and non-market sectors. The market and non-market damage estimates, including their distribution parameters and breakdown between the two sectors, are best described as based on author’s judgment informed by Nordhaus & Boyer (2000), Tol (1999), and Tol (2002a).
- ³⁴ In Page2002, only Eastern Europe could potentially reap climate benefits from temperature increases.
- ³⁵ For market damages, this temperature threshold increases with adaptation.
- ³⁶ Hope (2006) calibrates his discontinuous damage function parameters based on discussions in the IPCC (2001a) on pages 947 and 952. Specifically, Hope (2006) calibrates the parameters corresponding to the percentage GDP loss in Europe for a discontinuity and the tolerable temperature risk using general statements about discontinuous damages in the IPCC (2001a). This implies that Hope (2006) utilized his discretion to calibrate the discontinuous damage function parameters.
- ³⁷ See footnote 12 for a discussion of revealed and stated preference.
- ³⁸ Ecosystem services and secondary social effects (such migration) are for the most part excluded from IAMs.
- ³⁹ Note that FUND implicitly accounts for catastrophic damages; see footnotes 15 and 31. As a consequence, FUND may implicitly capture market and non-market catastrophic damages to the extent that the assumed probability distribution functions for uncertain parameters capture tipping points.
- ⁴⁰ With respect to FUND 3.6, Tol (2013) explicitly states: “Some impacts are missing altogether – air quality, violent conflict, labour productivity, tourism, and recreation. Weather variability is poorly accounted for, and potential changes in weather variability ignored. The model assumes that there are few barriers to adaptation. There are no interactions between the impact sectors, and therefore are no higher order effects on markets or development.”
- ⁴¹ Ocean acidification, wildfires, and pests, pathogens, and weeds affect the market sector via agriculture, forestry, and or fisheries and the non-market sector via biodiversity, ecosystem services, human health, and/or human settlements.
- ⁴² In many of the enumerative studies that do include fisheries, fisheries are abstractly captured under “other market” damages.
- ⁴³ See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

- ⁴⁴ Given the uncertainty of the effect of climate change on fisheries, Sumaila et al., (2011) argues that fisherman may increase their current fishing efforts given the possibility of lower future fishing stocks.
- ⁴⁵ Phytoplankton are essential to the ocean food web and the global climate system. In terms of the latter, “Marine phytoplankton are responsible for [approximately] 50 percent of the CO₂ that is fixed annually worldwide (Toseland et al., 2013).”
- ⁴⁶ For example, ozone emissions from fuels lower crop yields (Ackerman and Stanton 2011).
- ⁴⁷ Ozone impacts are counted separately in BCA analysis as traditional pollutants, not caused by climate change.
- ⁴⁸ The CO₂ fertilization effect in FUND 3.6 is drawn from studies that assume a fertilization effect based on enclosure experiments, as do the studies behind DICE-2013 that account for this effect. However, DICE-1999, and therefore to some extent PAGE09, and several of the other studies behind DICE-2013 exclude the CO₂ fertilization effect altogether.
- ⁴⁹ As discussed in Koetse and Rietveld (2009), some research casts doubt on the possibility of the Northwest Passage being a valid future shipping route.
- ⁵⁰ Due to lower water levels, substantial increases of inland water-way transportation costs are possible. High water levels due to heavy precipitation events can also result in river closures (Koetse and Rietveld, 2009).
- ⁵¹ Network effects are delays, detours, and cancellations due to disruptions in the transportation network. In other words, transportation costs may be incurred in areas not directly affected by an extreme event due the propagation of costs throughout the network. These costs may be substantial (Koetse and Rietveld, 2009).
- ⁵² Bigano et al. (2007) state that “world aggregate expenditures hardly change, first rising slightly and then falling slightly.” However, there is a considerable noise in the resulting estimates.
- ⁵³ As noted, DICE-2013 uses a combination of enumerative and statistical studies. While the statistical studies may capture some dynamic effects indirectly, all of these studies are cross-sectional in nature.
- ⁵⁴ As a consequence, Moyer et al., (2013) argues that DICE assumes a weak propagation of damages on growth.
- ⁵⁵ The modified version of DICE used by the IWG eliminates the potential effect of climate change on economic growth through how it models changes in the savings rate.
- ⁵⁶ The intuition is that mitigation spending in the present is equivalent to asking the current generation earning approximately \$50,000 per household to transfer money to a future generation in 2300 earning \$1.5 million per household (Moyer et al., 2013).
- ⁵⁷ This point is made by Dasgupta (2006) with respect to Nordhaus’ DICE model. “Despite the serious threats to the global economy posed by climate change, little should be done to reduce carbon emissions ... [Nordhaus’] idea is not that climate change shouldn’t be taken seriously, but that it would be more equitable (and efficient) to invest in physical and human capital now, so as to build up the productive base of economies (including, especially, poor countries), and divert funds to meet the problems of climate change at a later year. These conclusions are reached on the basis of an explicit assumption that global GDP per capita will continue to grow over the next 100 years and more even under business as usual, an assumption that the [Stern] Review would appear to make as well.” Given that the Stern Review utilized PAGE02, Dasgupta is in a sense making this point about PAGE as well.
- ⁵⁸ According Hope, it is possible in PAGE09 for climate change damages to be large enough to negatively affect consumption growth, such that the discount rate becomes negative (personal correspondence with Hope, 2014).
- ⁵⁹ While the Dell, Jones, & Olken (2012) estimate relies on annual data rather than medium-run or long-run average of temperature and precipitation, the authors do provide medium-run estimates that compare average growth rates between 1979 and 1985 and from 1985 to 2000. In these medium-run cases, they again find negative effects of higher temperatures on the growth rates of poor nations.
- ⁶⁰ Butkiewicz and Yanikkaya (2005) do find that the costs of social-political instability increase the higher the level of national income and democracy of a nation.
- ⁶¹ Higher temperatures require workers to take more breaks, work fewer hours, and/or decrease work intensity (i.e., slow down) (Kjellstrom et al., 2009).
- ⁶² While not discussed here, it is possible that as vector-borne diseases spread, more countries could become mired in poverty-disease traps, such as in current sub-Saharan Africa (Fankhauser and Tol, 2005).

- ⁶³ “The impacts on labor supply are non-trivial. If temperatures were to rise by 5 degrees Celsius in the United States by the end of the coming century and no adaptation occurs, U.S. labor supply would fall by roughly 0.6 hours per week in high-exposure industries, representing a 1.7 percent decrease in hours worked and thus earnings. In developing countries, where industrial composition is generally skewed toward climate-exposed industries and prevailing temperatures are already hotter than those in most of the United States, the economic impacts are likely to be much larger (Zivin & Neidell, 2010).”
- ⁶⁴ Modeling such changes in DICE may be difficult. On the one hand, Hall & Behl (2006) argue that “with irregular flickering between climate states, characteristic of past climatic transitions, we would expect the destruction of capital stock. If the flickering is forced by human activity, then policy or lack thereof results in the destruction of capital stock and a discontinuity of the rate of return on capital, violating the equilibrium condition.” On the other hand, computer general equilibrium models, including ICES and ENVISAGE, have no such problem. ICES and ENVISAGE do not model capital losses as shocks, but instead use expected losses (Bosello et al., 2012; Roson & van der Mensbrugghe, 2010).
- ⁶⁵ The simplicity of the Cass-Koopmans model is particularly useful for making generalizations about the impact of climate change on factor productivity and economic growth. However, this simplicity also ignores certain empirical realities of economic growth (Lecocq & Shalizi, 2007). For example, the Cass-Koopmans model assumes a single aggregate good, while economies consist of multiple industries that are possibility affected differently by climate change. In another example, the Cass-Koopmans model assumes a production function with constant returns to scale, whereas, an economy characterized by increasing returns to scale may become “trapped” at a low growth rate if climate change causes large and frequent shocks to capital or labor productivity or stocks (Aziadaris & Stachurski, 2005).
- ⁶⁶ In DICE, it could be argued that declines in labor and capital productivity are already captured by their expression for “climate damages as fraction of output.”
- ⁶⁷ Both the health and labor productivity damage sectors are effects on labor productivity. However, health effects are loss of labor productivity due to a decrease in labor stock through death and inability to work from disease, while the labor productivity damage sector accounts for decline in “on-the job” performance due to humidity and high temperatures.
- ⁶⁸ Like ENVISAGE, the authors of ICES model health damage as an effect on labor productivity.
- ⁶⁹ Environmental goods and services will become relatively scarcer than market goods and services due to climate change and other anthropomorphic drivers. As explained later in this subsection, because current damage estimates are estimated using willingness to pay estimates derived from data from the current time period, they fail to account for the future increases in the value of environmental goods relative to market goods due to the law of scarcity. By adopting structural modeling assumptions that also imply constant relative prices (i.e., that the relative value of non-market to market goods is constant over time), the developers of IAMs bias the SCC downward.
- ⁷⁰ Another example is disease regulation services, which are captured via health damage functions.
- ⁷¹ Another example is air quality regulation, which is partially captured in PAGE09 via the DICE-1999 damage function. DICE-1999 captures the health effects of air pollution, which is omitted from FUND altogether. DICE-2013 mostly likely omits this damage because Nordhaus and Boyer (2000) is only one of 13 studies utilized to calibrate its damage function.
- ⁷² Another example includes ecosystem services related to biochemicals, natural medicines, and pharmaceuticals.
- ⁷³ Another example is climate amenities, which includes cultural services, such as aesthetics, and outdoor leisure activities (i.e., non-market time use). Only earlier versions of DICE (i.e., DICE-1999 and DICE-2007) explicitly attempt to capture these services via Nordhaus’ estimate of non-market amenities. However, DICE-1999 only captures outdoor leisure activities, and omits all cultural values. However, even these estimates have come under considerable fire from Hanemann (1998) and Ackerman (2010).
- ⁷⁴ The assessment of damages on ecosystem services depends on a valuation of those services based on public WTP. Boyd and Krupnick (2009) and others have compared ecological and economic production systems, arguing that valuation of ecosystem services implies a valuation of their respective outputs. These “outputs” (e.g., reduced flood risk, flourishing fish populations) can be reliably understood and valued by the public in ways that specific ecosystem services (e.g., nutrient cycling) cannot. Because an individual values the endpoint and not the process itself, when asked to value a specific ecosystem service, an individual will base his WTP for the service on his WTP for the “output” of that service. Stated preference valuation that focuses on the value of specific services (instead of outputs) often prove inaccurate because those surveyed assume ecological production factors that may not be consistent with each other or with reality (Boyd & Krupnick, 2009).

- ⁷⁵ One such improvement could be to value the final outputs of species. In addition to their aesthetic and non-use values, analysis could estimate the value of the genetic material of species, an ecosystem service discussed in the previous subsection.
- ⁷⁶ In addition to his own criticism of how FUND values biodiversity, the model has also come under criticism by other economists. They argue that assuming that biodiversity loss is a function of temperature change, instead of temperature level, is incorrect because it implies ecosystem adaptation to climate change (Warren et al., 2006). As a consequence, ecosystem damages decline in the long run as temperature increases level off (Warren et al., 2006).
- ⁷⁷ This aggregate consumption good, often referred to as a numéraire, equals the combined economic values of all market and non-market goods divided by the global population.
- ⁷⁸ Constant relative prices imply that a decline in the supply of a consumption good (market or non-market) does not affect its price relative to all other goods and services. If the relative price of the good were to increase in response to this decline in supply, there would be no demand for the good because consumers could obtain more utility (i.e., welfare) by switching their expenditure to all other goods and services (due to the perfectly substitutable assumption). This would put downward pressure on the good's price until it reached its original value relative to all other prices.
- ⁷⁹ Discussions about changing relative prices date back to earlier literatures. Neumayer (1999) calls this argument the Krutilla-Fisher rationale from Krutilla and Fisher (1975). In the context of manufactured and public goods, Baumol (1967) describes a similar phenomenon called Baumol's disease. The discussion of changing relative prices also has roots in the earlier literatures of weak sustainability and strong sustainability.
- ⁸⁰ In this context, the elasticity of substitution measures the ease at which market goods can be substituted for non-market goods. An elasticity of substitution less than one implies that market goods and non-market goods are complements in the long run. In the extreme, perfect complements are when market goods cannot be substituted at any level to make up for the loss of non-market goods. An example would be subsistent water levels, where no amount of a market good can replace its value. An elasticity greater than one implies that market goods and non-market goods are substitutes (Heal, 2009). In the extreme, perfect substitutes are when market goods can be substituted at a constant rate to make up for a loss of non-market goods, regardless of the level of non-market goods available.
- ⁸¹ In the language of sustainability, an elasticity less than one implies strong sustainability in the long run. An elasticity greater than one implies weak sustainability in the long run.
- ⁸² It should be unsurprising that the discount rate requires updating because growth rates of man-made and environmental goods and services differ. In addition, the rationale for discounting, i.e., that the future will be better off due to continued economic growth, is weakened with the elimination of the perfect substitutability assumption.
- ⁸³ For example, the results can also apply to agricultural and non-agricultural goods. Heal (2009) argues that food shortages could result in the relative value of agricultural goods increasing from its currently insignificant level in most developed nations.
- ⁸⁴ Initially, Sterner and Persson (2008) assume that elasticity of substitution is equal to 0.5, 10 percent of current utility comes from non-market goods, and that 50 percent of damages are attributable to non-market goods. The remaining parameters follow the standard assumptions of DICE.
- ⁸⁵ The utility function chosen in Sterner and Persson (2008) assumes a constant elasticity of substitution, and implies only that a positive level of environmental services is essential (i.e., not zero).
- ⁸⁶ A small example of the possible magnitude of these relocation costs are Alaskan native villages. In the case of relocating three villages (Kivalina, Shishmaref, & Newtok), the cost is estimated by the U.S. Army Corps of Engineers to be between \$275 million and \$455 million. While these costs are high, they should be interpreted as an upper bound on costs due to the remoteness of these villages (Lynn & Donoghue, 2011).
- ⁸⁷ A decline in income may also decrease the opportunity cost of engaging in violence and civil conflict (Dell, Jones, & Olken, 2013).
- ⁸⁸ There is an argument in the literature that higher temperatures and extreme weather may not actually cause conflict, but actually just shifts future conflicts to the period of higher temperatures or more extreme weather. Hsiang, Meng, and Crane (2011) demonstrate that climate change will actually cause "new" conflicts, rather than just shifting the time periods of "existing" conflicts.

- ⁸⁹ While the studies vary in their focus over time and space, all 60 studies rely on the same general panel or time-series model. Cross-sectional studies and studies that control for confounding factors are avoided because these confounding factors are potential avenues through which climate can affect conflict. These 60 studies utilize 45 different conflict datasets. Two-thirds of these studies have been published since 2009.
- ⁹⁰ The number of inter-personal conflicts far exceeds inter-group conflicts. Thus, a smaller percentage increase in inter-personal conflicts than inter-group conflicts can result in a far greater increase in the number of inter-personal conflicts than inter-group conflicts.
- ⁹¹ Violence on an individual scale, such as increased aggression in the police force, can result in more inter-group conflict. Thus, these two types of conflicts are correlated, such that an increase in interpersonal violence can increase the possibility of intergroup conflict.
- ⁹² These 60 studies find that: an increase in temperature raises violent crime faster than it increases property crime; increases in precipitation increase personal and intergroup violence in poorer, agricultural-dependent communities; low and high temperatures and low water availability lead to organized political conflicts; windstorms and floods affect the level of civil conflicts; institutional breakdowns occur in developing economies when they become sufficiently climate stressed.
- ⁹³ These mechanisms include: decreased supply of resources leads to disagreements over their allocation; climate change makes conflict more appealing with regards to achieving a stated objective; declines in labor productivity make conflict relatively more desirable; declining state capacity reduces the ability of government institutions to suppress crime and provides incentives for competitors to increase the conflict; increased pressure for a redistribution of assets because of increased social and income inequality; increases in food prices; increasing migration and urbanization leading to conflict over geographically stationary non-climate related resources; changes in the logistics of human conflict increases incentives for conflict; a physiological response with respect to cognition, attribution, and/or aggression resulting from higher temperatures increases human propensity for conflict.
- ⁹⁴ Certainty equivalent catastrophic damages are the guaranteed magnitude of catastrophic climate damages that humanity finds equally desirable as (that is, is indifferent to) risky (that is, the unknown magnitude of) catastrophic damages that we currently face. Due to humanity's general aversion to risk, humans are willing to pay a premium to avoid risk.
- ⁹⁵ In DICE-2013, Nordhaus excluded damages from tipping points. Only two out of the 13 studies used include catastrophic damages. One of these studies, Hope (2006), does so at temperatures above the temperature used to calibrate the DICE-2013 damage function, that is, 2.5 degrees Celsius. As a consequence, the meta-analysis really only includes one study that accounts for tipping points. To rectify this shortcoming and *other omitted damages*, Nordhaus and Sztorc (2013) refit the damage curve after multiplying the damage estimates in Tol (2009) by 1.25. Specifically, Nordhaus and Sztorc (2013) state that "current studies generally omit several important factors (the economic value of losses from biodiversity, ocean acidification, and political reactions), extreme events (sea level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages)." Comparing the unadjusted and adjusted damage estimates (that is, estimates that do not and do assume a 25 percent increase in damages, respectively), Nordhaus and Sztorc (2013) implicitly assume omitted damages of 0.34 percent of GDP at 2.5 degree Celsius and 1.94 percent of GDP at 6 degree Celsius. In contrast, catastrophic damages in DICE-1999 are 1.02 percent at 2.5 degrees Celsius and 6.94 percent degrees Celsius according to Nordhaus and Boyer (2000), while they are 1.16 percent at 2.5 degrees Celsius and 4.72 percent at 6 degrees Celsius in DICE-2007; DICE-2010 makes the same assumption as DICE-2007. To achieve the levels of catastrophic damages observed in DICE-1999, Nordhaus and Sztorc (2013) would have used an adjustment of between 77 percent and 91 percent. Similarly, to achieve the catastrophic damages observed in DICE-2007, the authors would need to have chosen an adjustment of between 62 percent and 87 percent. Therefore, if we believe that the certainty equivalent measure of catastrophic damages is anywhere near the scale proposed in these earlier versions of DICE, the 25 percent increase by Nordhaus is nowhere near sufficient to account for the potential cost of tipping points in the climate system, let alone the *other omitted damages*.
- ⁹⁶ Nordhaus and Sztorc (2013), which is the source code for the default version of DICE-2013, specifies that the damage function is

where Δ is the percentage loss in GDP from climate tipping points and T is the global average surface temperature. However, the tipping point damage is turned off in the default version, implying that it is excluded in the catastrophic damage function. In Nordhaus (2013), the tipping-point damage function in his recent book (Chapter 18 – footnote 5) is

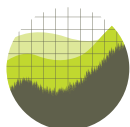
This appears to only be used in a very limited analysis, and Nordhaus (2013) states that this damage function is "at

the outer limit of what seems plausible and have no solid basis in empirical estimates of damages, so that should be interpreted as illustrating how tipping points might affect the analysis.”

- ⁹⁷ The first scenario could be driven by the accelerated increase in atmospheric GHG concentrations driven by the release of greenhouse gas stocks or by the reduced albedo (i.e., the reflectivity of the Earth’s surface) due to melting ice sheets. In either case, the rate of radiative forcing per unit of CO₂ is greater. The second tipping-point scenario is motivated by increased GHG atmospheric longevity due to the degradation of carbon sinks (e.g., forests, algae, and agricultural crops). Climate-driven dieback of trees in boreal and tropical forests or algae deaths would reduce Earth’s capacity to sequester carbon, effectively increasing the amount of time carbon lingers in the atmosphere by decreasing the decay rate of atmospheric carbon. More persistent carbon would then place carbon sinks under increased pressure, presumably decreasing the decay rate further.
- ⁹⁸ Anthoff and Tol (2013a) states that “FUND does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realizations are catastrophic.”
- ⁹⁹ “A Monte Carlo simulation will run an integrated assessment model thousands of times, each time randomly picking the value of uncertain parameters from a probability distribution function, i.e., a function that assigns a probability to each possible parameter value. For example, the Working Group ran 10,000 Monte Carlo simulations for each of the three IAMs and five socio-economic scenarios, randomizing the value of climate sensitivity, i.e., the change in average global temperature associated with a doubling of CO₂, and all other uncertain parameters in the IAMs by the original authors. For each randomly drawn set of values, the IAM estimated the associated damages, with the final SCC estimate equaling the average value across all 10,000 runs, five socio-economic scenarios, and then across all three models. Therefore, each SCC estimate is calculated using 150,000 runs (EDF, NRDC, Policy Integrity, and UCS comments, 2013).”
- ¹⁰⁰ These distributions, according to Anthoff and Tol (2013a), “are occasionally derived from meta-analyses of published estimates, but more often based on ‘expert guesses’.”
- ¹⁰¹ Specifically, Anthoff and Tol (2013a) state that “the fat tails found in the Monte Carlo analyses in FUND are a result, rather than an assumption.”
- ¹⁰² Pycroft et al., (2011) uses similar definitions of thin, medium, and fat tails as discussed earlier. To summarize, Pycroft et al., (2011) state that “thin-tailed probabilities, declining exponentially or faster; fat-tailed probabilities, declining polynomially or slower; intermediate-tailed probabilities, declining slower than exponentially but faster than polynomially.”
- ¹⁰³ Considering only the change in the climate-sensitivity parameter distribution from the default assumption in PAGE09 (i.e., the triangular distribution) to the three modified distributions, the PAGE09 SCC estimate increases from \$102 to \$131 (thin), \$146 (medium), and \$188 (fat); even larger percentage increases are observed for the 95th and 99th percentile SCC estimates. After accounting for a decline in the PAGE09 SCC estimate from \$102 to \$76 from turning off the catastrophic damage function, the SCC increases from \$76 to \$99 (thin), \$94 (medium), and \$114 (fat) when considering only changes in the distributions of the damage function exponents.
- ¹⁰⁴ See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.
- ¹⁰⁵ Yohe and Hope (2013) emphasize this concern. They warn that “to beware of analyses that are so narrow that they miss a good deal of the important economic ramifications of the full suite of manifestations of climate change; i.e., that they miss interactions in the climate system that allow climate change, itself, to be a source of multiple stress even within one particular sector.”
- ¹⁰⁶ Tol (2009) states that “In the enumerative studies, effects are usually assessed independently of one another, even if there is an obvious overlap—for example, losses in water resources and losses in agriculture may actually represent the same loss.”
- ¹⁰⁷ See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.
- ¹⁰⁸ In the statistical approach, analysts estimate climate damages using econometric techniques. While there are several identification strategies, which differ in method and types of climate damages captured, all econometric methods rely on current observations of the climate to estimate future climate damages.
- ¹⁰⁹ While trade is not a positive spillover per se, it is an inter-regional benefit that is only captured through the modeling of connections between regions.

- ¹¹⁰ Tradable goods represent only a fraction of market goods. They do not include market services, non-market goods and services, or market goods with prohibitively high transportation costs.
- ¹¹¹ Tol (2009) states: “In Bosello, Roson, and Tol (2007) and Darwin and Tol (2001), my coauthors and I show that sea level rise would change production and consumption in countries that are not directly affected, primarily through the food market (as agriculture is affected most by sea level rise through land loss and saltwater intrusion) and the capital market (as sea walls are expensive to build). Ignoring the general equilibrium effects probably leads to only a small negative bias in the global welfare loss, but differences in regional welfare losses are much greater.”
- ¹¹² Technology spillovers between nations do not guarantee that the worldwide cost of mitigation and adaptation will decrease.
- ¹¹³ In FUND 3.6, the number of migrants from the loss of dry land is equal to the product of land loss and average population density. The number of migrants between two regions is assumed to be a constant proportion of the overall number of migrants from the origin (sending) region: migrants from developed regions (United States, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, and the former Soviet Union) all resettle within their region of origin; 90 percent of migrants from developing regions (Middle East, Central America, South America, South Asia, Southeast Asia, China plus other nearby nations, North Africa, and sub-Saharan Africa) resettle within their region of origin, and the remaining 10 percent of migrants emigrate to developed regions; migrants from small island nations resettle in other regions: developed and developing (Anthoff and Tol, 2010).
- ¹¹⁴ Cline (1992) cites data showing that state and local government spending in 1989 was approximately \$3,000 per capita and assumes that immigrants do not pay taxes for their first 18 months in the United States and subsequently cover their share in state and local government expenditures. This yields an estimated cost per migrant of \$4,500, which was approximately 25 percent of U.S. per capita income in 1990; a 40 percent cost per migrant, as assumed by FUND, however, would correspond to a \$7,200 cost per migrant in the U.S. scenario. The average non-agricultural wage in the United States was \$17,994 in 1990 (Economic Report of the President, February 1991, 336 from Cline, 1992). The 40 percent figure likely comes from Fankhauser (1995; 50), who cites Cline (1992) in assuming that global warming will increase immigration by 17 percent worldwide; this figure from Cline (1992), however, was simply an illustration of the cost of migration to the United States and was hardly a “guesstimate,” as stated by Fankhauser. Further, Fankhauser applies the \$4,500 cost per migrant from Cline (1992) to estimate cost of migration to OECD countries, and follows Ayres and Walter (1991) in assuming a \$1,000 cost per migrant to non-OECD regions (Fankhauser, 1995; 51). The latter figure is based on foregone output a person would have produced had he or she not migrated. These assumptions are used to estimate a global cost of migration of \$4.33 billion (Fankhauser, 1995; 50), which is likely the source of the estimated cost of migration used in FUND.
- ¹¹⁵ See <http://www.economist.com/news/europe/21590946-bulgaria-struggling-cope-syrian-refugees-nightmare-all>.
- ¹¹⁶ See <http://www.bbc.co.uk/news/world-23813975>.
- ¹¹⁷ Freeman and Guzman (2009) state that “In addition to ecological changes, several of the other factors which contribute to the emergence of new diseases will very likely be exacerbated by global warming, including migration (as noted above) and breakdowns in public health infrastructures. It is impossible to say with certainty that climate change will result in new diseases—such emergences are highly complex, multi-factored developments—but it is very clear that climate change will substantially increase this risk.”
- ¹¹⁸ The United Nations’ Millennium Ecosystem Assessment states that “The loss of species and genetic diversity decreases the resilience of ecosystems, which is the level of disturbance that an ecosystem can undergo structure or functioning. In addition, growing pressures from drivers such as overharvesting, climate change, invasive species, and nutrient loading push ecosystems toward thresholds that they might otherwise not encounter. ... The most important direct drivers of change in ecosystems are habitat change (land use change and physical modification of rivers or water withdrawal from rivers), overexploitation, invasive alien species, pollution, and climate change.”
- ¹¹⁹ There are many threats to future water supplies other than climate change. First, many regions in the United States are currently overpumping their ground water (<http://ga.water.usgs.gov/edu/gwdepletion.html>). In developing nations, water withdrawals are expected to increase over the next 50 years (Millennium Ecosystem Assessment). Furthermore, water pollution and increased water demand due to a growing population are also issues.
- ¹²⁰ Given that gross revenue of marine captured fisheries (i.e., excluding aquaculture) equals approximately \$80 billion to \$85 billion annually globally (Sumaila et al., 2011), the effect on U.S. shellfish is small.
- ¹²¹ For example, the agricultural damage estimates used by Nordhaus include the benefits of farmer adaptation to climate change; see forthcoming Appendix A.
- ¹²² The adaptation assumptions underlying PAGE09 are more conservative than PAGE02. As a consequence, this downward bias is likely less significant for PAGE, as it is for the other two IAMs (Hope, 2006; Hope, 2011).

- ¹²³ This paper uses FUND 3.6 instead of FUND 3.8 as mentioned earlier; at the time this report was researched, documentation for FUND was only available up until FUND 3.6. Tol only made minor changes between versions 3.6 and 3.8. For the purposes of this report, no additional damages were included by the author.
- ¹²⁴ DICE-1999 and FUND 3.6, and PAGE09 as a consequence of being greatly informed by these two IAMs, exclude the value of firewood. The studies underlying the forestry damage estimates, i.e., Perez-Garcia et al., 1997; Sohngen et al., 2001, focus on industrial products manufactured from wood, but do not consider the use of wood for fuel. Perez-Garcia et al. (1997) note that fuel uses of wood accounted for roughly half of all timber harvests at the time of the study. Additionally, non-timber aspects of forests (e.g., recreation, water, wildlife, etc.) are only considered to the extent that they are captured in other sectors.
- ¹²⁵ It should be noted, however, that some of these categories also have damages associated with them that are omitted, such as increased energy supply costs due to increased weather variability and extreme events.
- ¹²⁶ Tol (2009) believes that unless a fundamental shift in the literature occurs, improving estimates of willingness to pay for biodiversity and ecosystem services will not affect the SCC. Citing Pearce and Moran (1994), he states that individuals are limited in their willingness to pay for conservation.
- ¹²⁷ This argument is based on statements by David Anthoff at the Cost-Benefit Analysis and Issue Advocacy Workshop on October 28, 2013 at New York University School of Law.
- ¹²⁸ This type of analysis does not represent new data or methodologies as discussed in the previous paragraph.
- ¹²⁹ Only DICE and FUND fail to account for the uncertainty in the functional form of damage equation.
- ¹³⁰ By utilizing the Ramsey discount rate equation, the three IAMs allow for declining discount rates resulting from declining economic growth rates. However, the 2010 and 2013 IWG estimates impose an external assumption of constant discount rates.



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Exhibit 17

Climate Risks and Carbon Prices: Revising the Social Cost of Carbon

Frank Ackerman and Elizabeth A. Stanton

Stockholm Environment Institute – U.S. Center, Somerville

Abstract The social cost of carbon – or marginal damage caused by an additional ton of carbon dioxide emissions – has been estimated by a U.S. government working group at \$21/tCO₂ in 2010. That calculation, however, omits many of the biggest risks associated with climate change, and downplays the impact of current emissions on future generations. Our reanalysis explores the effects of uncertainty about climate sensitivity, the shape of the damage function, and the discount rate. We show that the social cost of carbon is uncertain across a broad range, and could be much higher than \$21/tCO₂. In our case combining high climate sensitivity, high damages, and a low discount rate, the social cost of carbon could be almost \$900/tCO₂ in 2010, rising to \$1,500/tCO₂ in 2050.

The most ambitious scenarios for eliminating carbon dioxide emissions as rapidly as technologically feasible (reaching zero or negative net global emissions by the end of this century) require spending up to \$150 to \$500 per ton of reductions of carbon dioxide emissions by 2050. Using a reasonable set of alternative assumptions, therefore, the damages from a ton of carbon dioxide emissions in 2050 could exceed the cost of reducing emissions at the maximum technically feasible rate. Once this is the case, the exact value of the social cost of carbon loses importance: the clear policy prescription is to reduce emissions as rapidly as possible, and cost-effectiveness analysis offers better insights for climate policy than cost-benefit analysis.

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Keywords Social cost of carbon; cost-benefit analysis; climate policy; climate economics

Correspondence Frank Ackerman, Stockholm Environment Institute – U.S. Center, 11 Curtis Ave., Somerville, MA 02144, USA; e-mail: frank.ackerman@sei-us.org.

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1 Introduction

With the U.S. Environmental Protection Agency's recent historic step toward regulation of greenhouse gas emissions, cost-benefit analyses of proposed American regulations can now include an estimate of damages caused by greenhouse gas emissions – or conversely, the benefits of reducing those emissions. It is, however, a very small step: the “social cost of carbon” (SCC), i.e. the damage per metric ton of carbon dioxide (tCO₂), is estimated at \$21 for 2010, in 2007 dollars (Interagency Working Group 2010). Equivalent to \$0.21 per gallon of gasoline,¹ such a low cost seems to suggest that only modest, inexpensive measures are needed to address climate risks.²

The analysis by the federal Interagency Working Group is significant for its role in setting U.S. climate policy, and for its recognition that policy should be based on global, rather than domestic, impacts (unlike most national environmental policies). It is also noteworthy as a rare instance where economic theories and analyses have been newly introduced into the public policy debate.³ Thus it is important to examine the uses of climate economics in the Working Group analysis, particularly the treatment of the crucial uncertainties that characterize the field. This paper presents an examination and re-analysis of the SCC, finding that four major uncertainties in the economics of climate change could imply much larger estimates. In each case, the Working Group has chosen the option that minimizes estimates of climate risks and damages.

We begin with a discussion of the choice of models and scenarios for the SCC calculation. Our re-analysis relies on the Dynamic Integrated model of Climate

¹ According to the U.S. Environmental Protection Agency, there are 8.8 kg of CO₂ emissions from a gallon of gasoline, implying that 114 gallons of gasoline yield one metric ton of emissions (the standard unit for analysis of emissions); 103 gallons yield one short ton of emissions (see <http://www.epa.gov/oms/climate/420f05001.htm>, accessed April 22, 2011). Thus a useful rule of thumb is that \$1 per ton of CO₂ is equivalent to roughly \$0.01 per gallon of gasoline. The estimate in the text of \$0.21 per gallon is offered solely for the sake of comparison; there are no existing or proposed federal regulations that would add a carbon charge to the price paid for gasoline.

² On the implications of low SCC values, see Ackerman and Stanton (2010).

³ It is new only for U.S. policy; other countries, notably the United Kingdom, are several years ahead of the United States in this respect. The U.S. policy process is unfortunately parochial, however, so that the introduction of climate economics into American policy analysis is presented with almost no reference to other countries' experience.

and the Economy (DICE), one of the models used in the Interagency Working Group analysis that produced the \$21/tCO₂ estimate. We use the Working Group's modified version of DICE, the same five scenarios on which they based their calculations, and the same framework of Monte Carlo analysis.

We then introduce four major areas of uncertainties that affect the calculation: the sensitivity of the climate to greenhouse gases; the level of damages expected at low temperatures; the level of damages expected at high temperatures; and the discount rate. We recalculate the SCC based on combinations of high and low alternatives for each of these factors, yielding an array of 16 values, both for 2010 and for 2050.

Some of the resultant values for the SCC are extremely high; the highest ones are close to \$900/tCO₂ in 2010 and \$1,500 in 2050. In contrast, a review of scenarios that reach zero or negative net global emissions within this century finds that they often imply carbon prices, and marginal abatement costs, of \$150 to \$500/tCO₂ by 2050. Many of our alternative SCC values are within or above this range – and still would be, even if recalculated on a low-emissions scenario.

We conclude with a discussion of the meaning of very high SCC estimates. Once the SCC reaches or exceeds the cost of bringing net emissions to zero, its exact value becomes less important; if the SCC were twice as large, it would have the same policy implications. At such high SCC values, cost-benefit analysis of individual policies provides no useful information; what is needed instead is a cost-effectiveness analysis of the least-cost, most efficient pathway to reach zero or negative net emissions.

2 Choice of Models

The Interagency Working Group used three well-known models of climate economics: DICE, Policy Analysis of the Greenhouse Effect (PAGE), and Framework for Uncertainty, Negotiation and Distribution (FUND).⁴ They ran each of the models on the same five scenarios, in Monte Carlo mode, examining the effects of a range of values for climate sensitivity and (in PAGE and FUND) many

⁴ For a description of DICE, see Nordhaus (2008); for PAGE, see Hope (2006a); for FUND, see Anthoff and Tol (2009).

other uncertainties. Under their “central case” – the mean value at a 3 percent discount rate – the value of the SCC, averaged across the five scenarios, was \$28/tCO₂ in DICE, \$30 in PAGE, and \$6 in FUND, for a three-model average of \$21.

Our re-analysis uses only the DICE model, which is the easiest of the three to modify for our purposes. As suggested by the Working Group’s central case results, it is likely that FUND would have produced lower estimates than those reported below, while PAGE would have produced higher estimates. Regarding the latter, PAGE has an explicit treatment of potential climate catastrophes, using a Monte Carlo analysis that allows variation in the size of catastrophes, the temperature threshold at which they become possible, and the likelihood of catastrophe once the threshold has been passed. DICE, in contrast, includes the certainty-equivalent or expected value of catastrophe in its damage function. As a result, PAGE estimates a higher SCC than DICE at lower discount rates or higher climate sensitivity.⁵ Our analysis includes both lower discount rates and higher climate sensitivity, so our SCC estimates would have been higher if we had used PAGE.

3 Choice of Scenarios

The Working Group analysis rejects the widely used Intergovernmental Panel on Climate Change (IPCC) climate scenarios, and instead uses scenarios from four other models: the business-as-usual scenarios from IMAGE, MERGE, MESSAGE, and MiniCAM, and a 550 ppm stabilization scenario.

It is difficult to interpret the inclusion of the 550 ppm scenario. Does it imply a guess that under business-as-usual conditions, there is a 20-percent chance that the world will reach agreement on stabilization at that level? No explanation is offered. Moreover, the 550 ppm scenario is not even a single, internally consistent scenario; rather, its GDP, population, and emissions trajectories are averages of the

⁵ A lower discount rate increases the importance of events farther in the future, when temperatures are higher and catastrophes are more likely. Higher climate sensitivity makes higher temperatures and increased risks of catastrophe occur sooner. For these reasons, PAGE estimates a larger SCC than DICE at a 2.5-percent discount rate, and at 95th percentile climate sensitivity; see Interagency Working Group on Social Cost of Carbon (2010), Table 3.

values in the 550 ppm scenarios from the other four models (see Interagency Working Group 2010, 16).

Nonetheless, inclusion of the 550 ppm scenario makes little difference in practice. Excluding it would cause only a \$1 increase to the \$21/tCO₂ SCC average estimate from DICE, FUND, and PAGE, or the \$28 estimate from DICE alone. For the ensemble of 16 SCC estimates in our analysis, presented below, exclusion of the 550 ppm scenario would cause an average increase of less than 4 percent; all of our estimates would change by less than 17 percent in either direction.

The four business-as-usual scenarios used by the Working Group were adopted from an Energy Modeling Forum (EMF) model comparison exercise (Clarke et al. 2009). For those who are not familiar with EMF, it may be helpful to contrast the selected EMF scenarios with the IPCC's SRES scenarios.⁶ Figure 1 and Figure 2 compare the cumulative carbon dioxide emissions and current methane emissions from the four EMF scenarios and three IPCC scenarios, A2, B2, and B1.⁷ As Figure 1 shows, carbon dioxide emissions in the four EMF scenarios (solid lines) are close to the B1 and B2 scenarios for the first half of this century, spreading out to roughly span the interval from A2 to B2 by 2100.

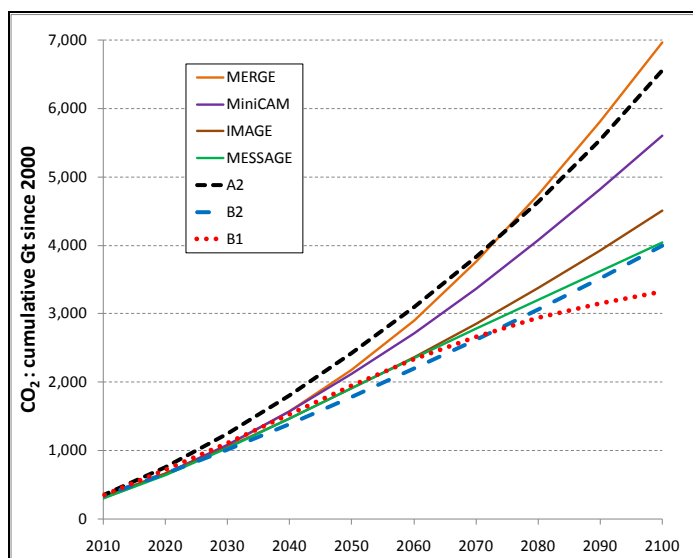
For methane emissions, Figure 2 shows that three of the four EMF scenarios start out well below the level of the B1 and B2 scenarios; by 2100, all four are roughly at or below the level of B2. In short the emissions trajectories of the EMF scenarios are broadly within, but toward the lower end of, the spectrum of IPCC SRES scenarios, perhaps closest to B2.

All else being equal, lower emissions usually imply lower temperatures, lower damages, and therefore a lower estimate of the SCC (for a discussion of countervailing factors see section 7). Use of a scenario in which emissions grow more rapidly, such as A2, would likely have led to higher values for the SCC.

⁶ IPCC scenario data are from http://sres.ciesin.org/final_data.html , downloaded March 1, 2011. EMF scenario data are from http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures , downloaded February 15, 2011.

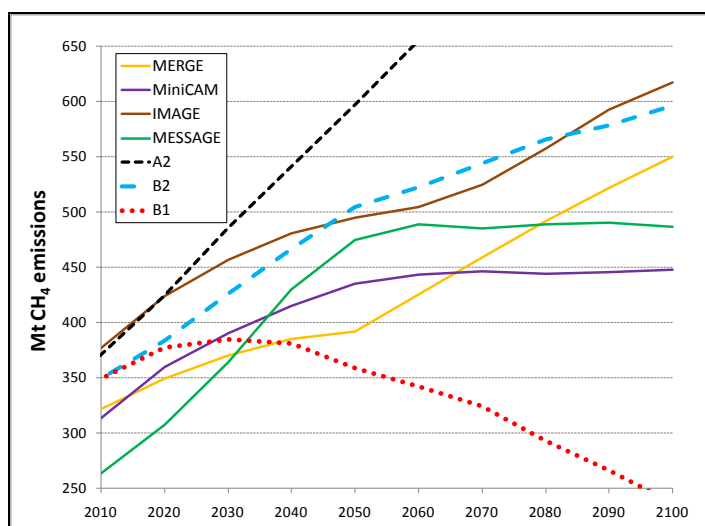
⁷ Figure 1 presents cumulative emissions because CO₂ persists in the atmosphere for long periods of time; Figure 2 presents current emissions because methane is removed from the atmosphere much more quickly.

Figure 1: Comparing EMF and IPCC CO₂ emission scenarios



Source: See text.

Figure 2: Comparing EMF and IPCC CH₄ emission scenarios



Source: See text.

For the sake of comparability with the Working Group results, we have adopted the same five scenarios in our analysis of uncertainties. Kopp and Mignone (2011) provide a more detailed evaluation of the Working Group's emission scenarios as part of a discussion of the full set of assumptions used in the Working Group's analysis.

4 Four Uncertainties

This section explores four major uncertainties that affect the SCC calculation: the value of the climate sensitivity parameter; the level of climate damages expected at low temperatures; the level of damages at high temperatures; and the discount rate. Section 5 presents multiple estimates of the SCC, based on alternatives for each of these uncertainties.

4.1 Climate Sensitivity

The climate sensitivity parameter is the long-term temperature increase expected from a doubling of the concentration of carbon dioxide in the atmosphere. This crucial parameter, which measures the pace of global warming, remains uncertain, and there are reasons to believe that significant uncertainty about climate sensitivity is inescapable (Roe and Baker 2007).

On this topic, the Working Group analysis is impressively thorough. They discuss the scientific evidence on likely values of climate sensitivity, and adopt a probability distribution which assumes a two-thirds probability that climate sensitivity is between 2.0°C and 4.5°C. The minimum is zero and the maximum is 10°C; the distribution has a median of 3.0°C and a 95th percentile of 7.14°C. They then perform a Monte Carlo analysis, repeatedly selecting a climate sensitivity value from this probability distribution. In PAGE and FUND, there are numerous other Monte Carlo variables, representing other uncertainties; in DICE, normally a deterministic model, climate sensitivity is the only Monte Carlo variable in the Working Group analysis.

The Working Group reports, but does not emphasize, the 95th percentile results. For DICE in particular, those results are a measure of the potential impact

of uncertainty about climate sensitivity. Results for DICE, and for the three-model average used by the Working Group, are presented in Table 1.

We follow the Working Group in calculating average and 95th percentile SCC results over 10,000 iterations, using the same probability distribution for climate sensitivity as the Working Group, in each of the five climate scenarios for each of the variations described below. In DICE, the average and 95th percentile results may correspond to climate sensitivity somewhat below 3.0°C and 7.14°C, respectively, since actual climate sensitivity in DICE (and several other integrated assessment models) is lower than the reported values. DICE uses a default climate sensitivity of 3.0°C, but actually responds to a doubling of atmospheric carbon dioxide with a long-run temperature increase of 2.77°C (van Vuuren, Lowe, et al. 2011).

Table 1: SCC estimates, 2010 and 2050, 3% discount rate

Emissions year	Result	DICE	3-Model Average
2010	Average	\$28	\$21
2010	95 th percentile	\$56	\$65
2050	Average	\$64	\$45
2050	95 th percentile	\$123	\$136

Source: Interagency Working Group (2010). For DICE, average and 95th percentile results are based on the probability distribution for climate sensitivity. For PAGE and FUND, the corresponding results refer to the entire Monte Carlo analysis, including uncertainty about other parameters as well as climate sensitivity.

4.2 Damage Function Estimates

Like climate sensitivity, the relationship between temperature increases and economic damage is uncertain. The Working Group says little about the estimates of economic damages from climate change, except to call for additional research. Kopp et al. (2011) modify the Working Group's version of the DICE model by including uncertainty in the damage function and varying the level of risk aversion

in the discount rate. We take a simpler approach: the damage function remains a certainty equivalent, but we explore alternative functional forms and parameter values.

DICE assumes that as temperatures rise, an increasing fraction of output is lost to climate damages. We will use D for damages as a fraction of the GDP that would be produced in the absence of climate change; $R = 1 - D$ for the net output ratio, or output net of climate damages as a fraction of output in the absence of climate change; and T for global average temperature increase in °C above 1900. The DICE damage function is:

$$(1) \quad R = 1 / (1 + .00284 T^2)$$

Or equivalently,

$$(2) \quad R = 1 / [1 + (T / 18.8)^2]$$

The DICE net output ratio can be viewed as combining two separate estimates: first, for low temperatures, William Nordhaus, the creator of DICE, estimates that damages are 1.7 percent of output at 2.5°C (Nordhaus 2007); second, at high temperatures, it is assumed by default that the quadratic relationship of damages to temperature in (1) or (2) continues to apply. Separate research addresses the low-temperature and high-temperature estimates, suggesting alternatives to each.

The DICE low-temperature damage estimate is based on an evaluation of several categories of climate damages at 2.5°C (Nordhaus 2008; Nordhaus and Boyer 2000). In a review and critique of the Nordhaus estimates as applied to the United States, Michael Hanemann develops alternative estimates for damages at 2.5°C, which are, in total, 2.4 times the Nordhaus value (Hanemann 2008).⁸ If the same relationship applies worldwide, then a reasonable alternative at low

⁸ Hanemann compares his calculations to an earlier version of DICE; Hanemann's estimate is 4.0 times the DICE-99 estimate, or 2.4 times the DICE-07 estimate, of damages at 2.5°C.

temperatures is to keep the form of equation (1) or (2), but recalibrate damages to 4.2 percent of output at 2.5°C. This yields the equation:

$$(3) \quad R = 1 / [1 + (T / 12.0)^2]$$

Neither the Nordhaus nor the Hanemann 2.5°C estimate provides a basis for projecting damages at much higher temperatures.⁹ It has become conventional to extrapolate the same quadratic relationship to higher temperatures, but there is no economic or scientific basis for that convention. The extrapolation implies that damages grow at a leisurely pace, especially in the Nordhaus version: from equations (2) and (3), it is easy to see that half of world output is not lost to climate damages until temperatures reach almost 19°C according to DICE, or 12°C in the Hanemann variant.

In a discussion of damage functions and catastrophic risks, Martin Weitzman argues that even if the Nordhaus estimate is appropriate for low-temperature damages, the increasingly ominous scientific evidence about climate risks implies much greater losses at higher temperatures (Weitzman 2010). He suggests that damages should be modeled at 50 percent of output at 6°C and 99 percent at 12°C as better representations of the current understanding of climate risks; the latter temperature can be taken as representing the end of modern economic life, if not human life in general. In support of this disastrous projection for 12°C of warming, Weitzman cites recent research showing that at that temperature, areas where half the world's population now lives would experience conditions, at least once a year, that human physiology cannot tolerate – resulting in death from heat stroke within a few hours (Sherwood and Huber 2010).

Weitzman creates a damage function that matches the DICE estimate at low temperatures, but rises to his suggested values at 6°C and 12°C. He modifies (2) by adding a higher power of T to the denominator:¹⁰

⁹ Nordhaus presents some numerical estimates of damages at 6°C, suggesting they are between 8 percent and 11 percent of output (Nordhaus 2007); these estimates are not well documented, and do not appear to be used in the calibration of DICE.

¹⁰ This equation follows Weitzman's method but differs slightly from his numerical estimates. He appears to have taken the DICE coefficient in (1) to be .00239 rather than .002839. Our equations (4)

$$(4) \quad R = 1 / [1 + (T / 20.2)^2 + (T / 6.08)^{6.76}]$$

When T is small, the quadratic term in (4) is more important, providing a close match to the original DICE damage function; when T is large, the higher-power term is more important, allowing the damage function to match Weitzman's values for higher temperatures.

The same method can be applied to the Hanemann low-temperature estimate in (3); calibrating to Hanemann's value at 2.5°C, and Weitzman's values at 6°C and 12°C, we obtain:

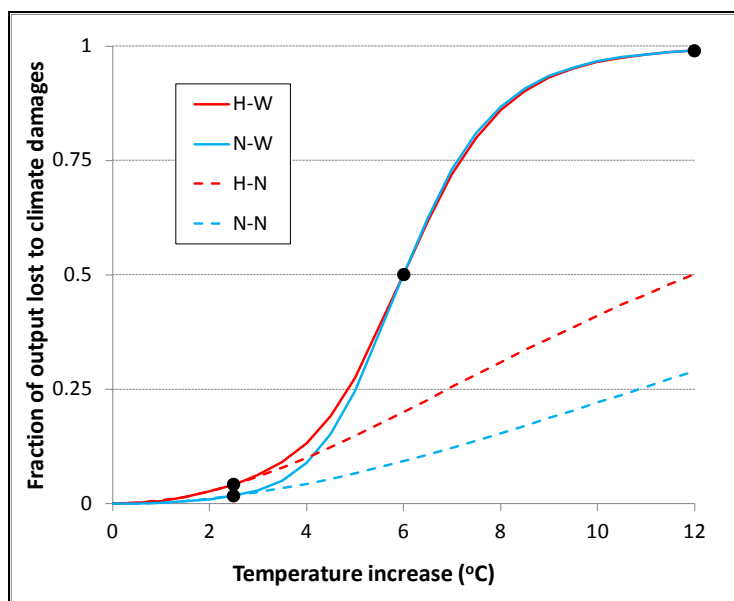
$$(5) \quad R = 1 / [1 + (T / 12.2)^2 + (T / 6.24)^{7.02}]$$

Equations (2), (3), (4), and (5) incorporate all combinations of two low-temperature alternatives (Nordhaus and Hanemann), and two high-temperature alternatives (Nordhaus and Weitzman). Using their initials, these can be labeled as the N-N, H-N, N-W, and H-W damages functions, respectively. They are displayed in Figure 3 (the graph presents damages as a share of GDP, i.e. $D = 1 - R$), with large dots indicating the points used for calibration. Below 3°C, the low-temperature alternatives are dominant, and the high-temperature alternatives make no visible difference; at 6°C and above, the high-temperature alternatives determine the shape of the damage function. In particular, the two damage functions with the Weitzman high-temperature assumption are nearly identical above 6°C.¹¹

and (5) were fitted to minimize the sum of squared deviations from the Nordhaus and Hanemann damage estimates, respectively, at 2.5°C, and the Weitzman point estimates at 6°C and 12°C.

¹¹ A small anomaly is that between 6°C and 12°C the N-W damage function, despite its lower low-temperature damages, is slightly higher than H-W; the gap is widest at 6.9°C, where N-W damages are 1.5 percent above H-W.

Figure 3: Damages as a share of GDP in four damage functions



Source: Authors' calculations.

4.3 Discount Rates

The Working Group's analysis of the SCC is based on projected costs and benefits extending 300 years into the future, as is our reanalysis. Across such spans of time, the discount rate is crucial to the bottom-line evaluation: the lower the discount rate, the more important the outcomes in later years will be. It seems safe to say that there is ongoing controversy and a lack of consensus on the appropriate discount rate to use in climate economics.

The Working Group discusses the discount rate at length, justifying their choice of a fixed rate of 3 percent. This is one of the discount rates normally recommended for use in U.S. government policy analyses. It can be supported within either of the two frameworks used to determine the discount rate, the descriptive and prescriptive approaches (Arrow et al. 1996). The descriptive approach calls for use of an appropriate market interest rate; the Working Group estimates the real risk-free rate of return, after tax, at 2.7 percent. The prescriptive

approach deduces the discount rate from first principles, as the sum of “pure time preference” (the discount rate that would apply if per capita consumption were constant) plus a multiple of the rate of growth of per capita consumption. The Working Group concludes that “arguments made under the prescriptive approach can be used to justify discount rates between roughly 1.4 and 3.1 percent” (Interagency Working Group 2010, 23), and expresses skepticism about the lower end of that range.

Both descriptive and prescriptive arguments can be made for discount rates below 3 percent. The long-term average risk-free rate is often estimated to be lower than 2.7 percent.¹² In addition, if climate mitigation, like insurance, is most valuable in circumstances that reduce incomes, then the discount rate should be lower than the risk-free rate of return. Using the prescriptive approach, the Stern Review spells out in detail the arguments for a low discount rate, on grounds of intergenerational equity (Stern 2006). Stern’s recommended formula for the discount rate is 0.1 percent plus the rate of growth of per capita consumption; this implies an average of 1.4 percent per year, in the Stern Review’s model.

To explore the effect of discount rates on the SCC, we use two rates, 3 percent and 1.5 percent per year – approximating the range that the Working Group identified as supportable under the prescriptive approach (as quoted above). Our lower rate is close to the Stern Review’s rate; moreover, it is the average rate that would result from applying Stern’s formula, 0.1 percent plus the rate of growth of per capita consumption, to the first 200 years of the Working Group’s four business-as-usual scenarios.¹³

¹² Since World War II, real returns have averaged 1.4 percent per year on Treasury bills and 1.1 percent on government bonds (DeLong and Magin 2009).

¹³ The EMF scenarios adopted by the Working Group have variable rates of growth by region and time period throughout the scenarios. Using Stern’s formula, or any version of the prescriptive approach, this should call for a time-varying, often declining discount rate. We follow the Working Group’s practice of using a fixed discount rate, for the sake of comparability with their results and minimization of changes to their version of the DICE model.

5 Results

The previous section identified two alternatives for each of four major factors influencing the SCC:

- Average versus 95th percentile climate sensitivity
- Nordhaus versus Hanemann damage estimates at low temperatures
- Nordhaus versus Weitzman damage estimates at high temperatures
- 3.0 versus 1.5-percent fixed discount rate

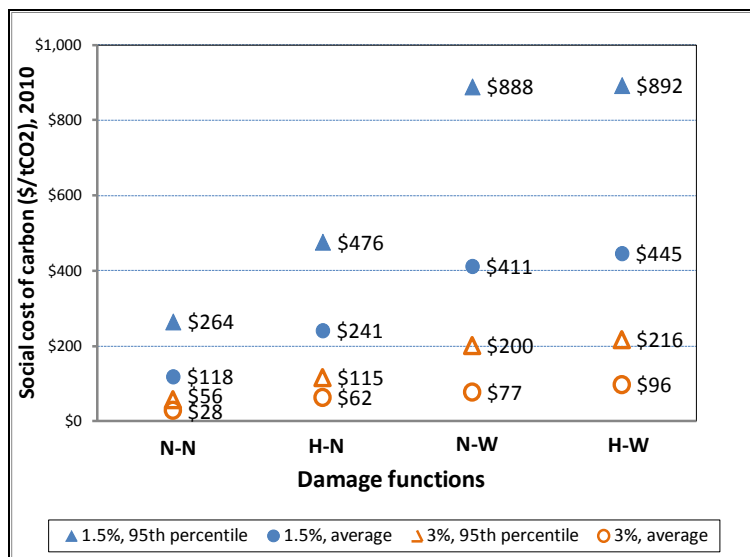
We calculated the SCC under each combination of these alternatives, making no other changes to the Working Group's version of DICE.¹⁴ This involved re-running the Monte Carlo analysis, with 10,000 iterations sampling the same probability distribution for climate sensitivity used by the Working Group, for each of the four damage functions shown in Figure 3, the 1.5 and 3.0-percent discount rates, and the five EMF climate scenarios. The results are shown in Figure 4 for 2010, and Figure 5 for 2050. Circles represent average climate sensitivity, and triangles 95th percentile; solid blue symbols represent 1.5-percent discount rates, and outlined orange symbols 3-percent. Results for the four damage functions are shown in four columns on the graphs, as marked.

The SCC is generally higher for later years, since GDP, as well as atmospheric concentrations of greenhouse gases, and temperatures, will be higher at that time – implying that the incremental damage from another ton of carbon dioxide emissions will be greater as well. So it is not surprising that the SCC estimates for 2050 are much higher than the corresponding figures for 2010.

In both graphs, the N-N (original DICE) damage function leads to lower estimates than any of the alternatives. If Hanemann is right about low-temperature damages, then the SCC in 2050 is above \$100/tCO₂ at a 3-percent discount rate, or about \$400 at 1.5 percent. If Weitzman is right about high-temperature damages, the mid-century SCC is above \$200 at a 3-percent discount rate, or above \$700 at 1.5 percent. At either discount rate, the estimates with Weitzman high-temperature

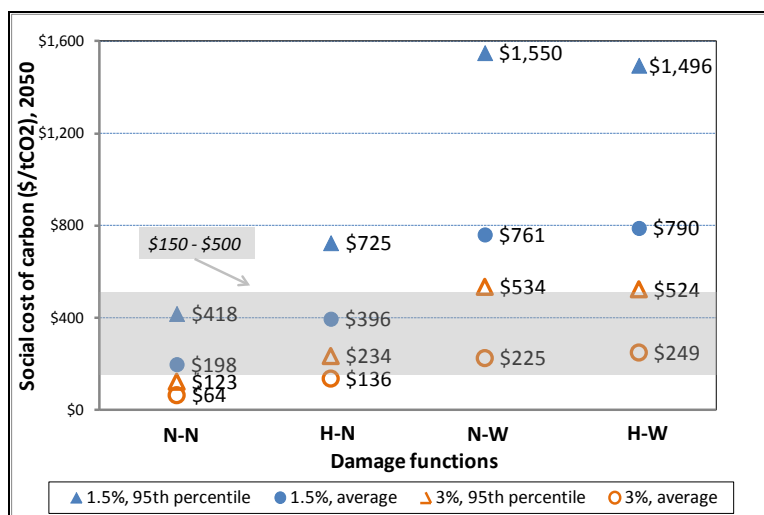
¹⁴ Thanks to Steve Newbold for making the Working Group's modified version of DICE available for independent analysis. We used the Working Group's DICE code, written in MatLab, with no modifications other than those described in this article.

Figure 4: Estimates of the SCC in 2010



Source: Authors' calculations, in 2007 dollars.

Figure 5: Estimates of the SCC in 2050



Source: Authors' calculations.

damages and 95th percentile climate sensitivity are almost four times higher than the N-N (original DICE) 95th percentile values, and seven to eight times higher than the N-N average values.

6 Abatement Costs

In a cost-benefit analysis of climate policy, the costs of doing nothing about climate change – i.e., the SCC – should be compared to the costs of doing something to mitigate it – i.e., the cost of reducing emissions. In several ambitious scenarios for drastic reduction in global emissions, the marginal cost per ton of abatement is lower than many of the SCC estimates presented above.

An inter-model comparison project, run by researchers at the Postdam Institute for Climate Change Research (PIK) in Germany, compared scenarios from five models that stabilize carbon dioxide concentrations at 400 ppm by 2100.¹⁵ Because carbon dioxide remains in the atmosphere for decades or centuries, and we are already at 390 ppm, these scenarios have to achieve negative net global emissions before 2100, through measures such as reforestation and biomass burning with carbon capture and sequestration (CCS). In general, the 400 ppm scenarios strain the limits of plausible rates of technological and socioeconomic change. Their carbon prices reach \$150-\$500/tCO₂ by 2050, with an average of \$260.¹⁶

A similar, though slightly more pessimistic, scenario from the International Energy Agency (IEA), stabilizes the atmosphere at 450 ppm of CO₂. This scenario – IEA’s “BLUE Map” – again strains the limits of possible technical change, and is meant to represent the maximum feasible pace of abatement. The marginal abatement cost in 2050 is between \$175 and \$500/tCO₂, depending on the degree of technological optimism or pessimism in cost forecasts (IEA 2008; 2010).

A more optimistic variant on this theme, from McKinsey & Company, projects rapid abatement leading to eventual stabilization at 400 ppm CO₂-equivalent;

¹⁵ See Edenhofer et al. (2010); Kitous et al. (2010); Magne et al. (2010); Leimbach et al. (2010); Barker and Scricciu (2010); and van Vuuren et al. (2010).

¹⁶ All dollar figures for abatement costs in this section are in 2005 dollars, roughly comparable to our SCC estimates in 2007 dollars; U.S. consumer prices increased 6 percent from 2005 to 2007.

atmospheric concentration peaks at 480 ppm CO₂-e in the 2060s before declining. McKinsey estimates the marginal abatement cost of this scenario at \$90-\$150/tCO₂-e in 2030 (McKinsey & Company 2009).

The British government assigns values to carbon emissions for use in long-term policy appraisals. Its estimates are based on marginal abatement costs under scenarios that are consistent with staying under 2°C of warming – which, in practice, is close to the maximum technically feasible pace of abatement. Their estimated carbon value for 2050 is £200 ± £100/t CO₂-e (U.K. Department of Energy & Climate Change 2009). At mid-2011 exchange rates, £100-£300 is equivalent to about \$165-\$495.

Comparing these abatement cost estimates to our SCC calculations, the low-stabilization-trajectory scenarios compared by PIK, the IEA BLUE Map, and the UK government carbon values all imply abatement costs of roughly \$150 to \$500/tCO₂ by 2050 – the region shaded in gray in Figure 5. Only three of our 16 SCC estimates for 2050 are below this range; all three assume Nordhaus (lower) high-temperature damages and a 3-percent discount rate. Eight of our estimates are within or barely above this range, and five are well above it. All of the top five assume a 1.5-percent discount rate, and four of the five assume Weitzman high-temperature damages.

The McKinsey estimate of the marginal cost for rapid abatement, \$90-\$150/tCO₂ in 2030, is a range that has already been reached or exceeded by most of our SCC estimates for 2010. Four of the eight estimates for 2010 at a 3-percent discount rate, and all eight of the estimates for 2010 at 1.5 percent, are at or above the McKinsey marginal abatement cost estimate for 2030.

In short, if either low-temperature or high-temperature damages are worse than DICE assumes, then the SCC is roughly at the marginal abatement cost for a maximal abatement scenario at a 3-percent discount rate, or well above that level at a 1.5-percent discount rate. Even with the original DICE damage function, the SCC estimates at a 1.5-percent discount rate are roughly comparable to the marginal cost of a maximal abatement path.

7 Sensitivity Analysis: SCC Estimates with Low Emissions

It would be possible to raise the objection that the comparison presented here is inappropriate: we compare the SCC, estimated on relatively high emissions scenarios, to marginal abatement costs of ambitious mitigation scenarios with much lower emissions. If the SCC were re-estimated on a rapid abatement trajectory, where marginal abatement costs reach \$150 to \$500/tCO₂ by 2050, would the SCC still equal or exceed this range?

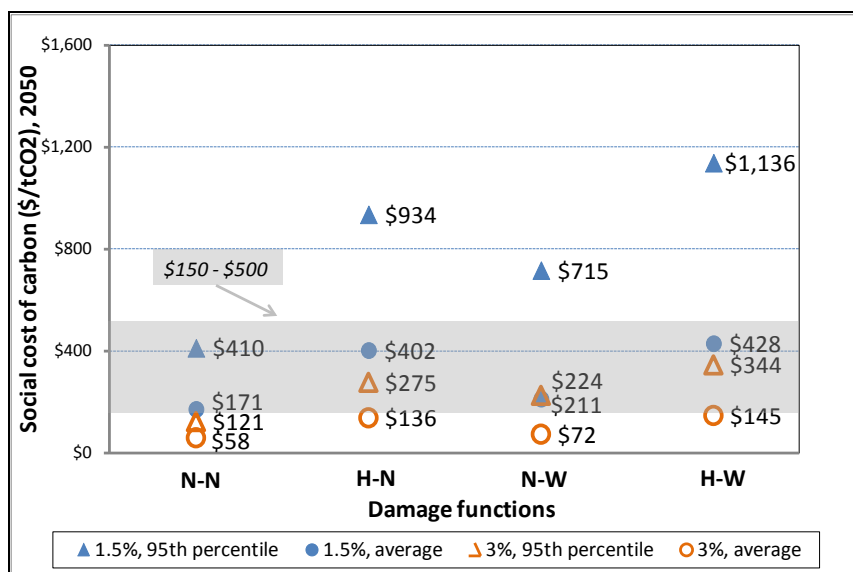
To test this possibility, we replaced the CO₂ emissions and non-CO₂ forcings in all five DICE scenarios with the corresponding data for the IPCC's new RCP2.6 scenario (also called RCP3-PD).¹⁷ RCP2.6 is designed to represent the emission reductions required to reach the widely discussed target of keeping temperature increases under 2°C; it projects more than 95 percent reduction in annual emissions of all greenhouse gases by 2100, and implies marginal abatement costs of around \$160 per ton of CO₂ in 2050 (van Vuuren, Stehfest, et al. 2011).

Our use of the RCP2.6 emissions and forcings is a sensitivity analysis, not a complete implementation of the RCP2.6 scenario assumptions. Specifically, we left GDP and population projections unchanged in all five of the Working Group's DICE scenarios, and assumed constant annual emissions and forcings after 2100. Nonetheless, recalculation of our results with RCP2.6 emissions and forcings provides a good test of the sensitivity of SCC estimates to emissions trajectories. The results for 2050 with RCP 2.6 emissions are shown in Figure 6, which can be compared to Figure 5, our 2050 results with the Working Group emissions trajectories.

The estimates with the N-N (original DICE) damage function are relatively little changed; they are only 2 to 14 percent smaller with the drastically lower RCP2.6 emissions, compared to the Working Group scenarios. This is consistent with the findings of Hope (2006b), who demonstrates that the SCC is insensitive to variations in emissions trajectories in the PAGE model. Hope's explanation is that two opposite effects are roughly equal in importance. On the one hand, radiative forcings, and therefore temperatures, are proportional to the logarithm of

¹⁷ Data downloaded from <http://www.iiasa.ac.at/web-apps/tnt/RcpDb> , December 2011.

Figure 6: Estimates of the SCC in 2050 with RCP2.6 emissions



atmospheric concentrations of greenhouse gases; this implies that at lower concentrations, a given increase in emissions causes a greater increase in temperature. On the other hand, damages increase more than linearly with temperature; this implies that at higher concentrations and temperatures, a given increase in temperature causes a greater increase in damages.

While these two effects will always work in opposite directions, the near-equality in their magnitude found by Hope (2006b) appears to depend on the assumed shape of the damage function. Our N-N damage function may be the closest, among our four options, to the PAGE damage function used in that analysis.

Our results with the H-N damage function are, counterintuitively, unchanged or higher with RCP2.6 emissions (Figure 6) than with the Working Group scenarios (Figure 5). This reflects a small anomaly in the data. While RCP2.6 emissions become sharply lower by late in this century, and remain very low thereafter, they do not start out below the Working Group scenarios. Under RCP2.6, CO₂ emissions are close to the average of the five Working Group scenarios for the first three decades; and RCP2.6 non-CO₂ forcings are well above

the Working Group scenario average for the first five decades.¹⁸ The H-N damage function uses our higher assumption about low-temperature damages, which would result from early emissions, but our lower assumption about high-temperature damages, which result primarily from later emissions. Thus its results are the most affected by the initial years when the RCP2.6 trajectory is at or above the Working Group scenario average.

Conversely, the N-W damage function is less sensitive to low-temperature damages and early emissions, but more sensitive to high-temperature damages and later emissions. The RCP2.6 reduction in later emissions has the greatest effect here, with all four N-W SCC estimates in Figure 6 at less than half of the corresponding levels in Figure 5. The H-W damage function is, in this respect, an intermediate case; the H-W SCC estimates are reduced by roughly one-quarter to one-half under RCP2.6, compared to the Working Group emissions.

The bottom line is that even with the rapid emission reductions projected under RCP2.6, our SCC estimates are at or above the estimated marginal abatement cost for a maximal abatement strategy (\$150 - \$500/tCO₂) in 11 of the 16 cases, as seen in Figure 6. The worst cases, involving 95th percentile climate sensitivity, a 1.5-percent discount rate, and any damage function except N-N, are all above \$700/tCO₂. At the other extreme, the only cases with SCC below \$100/tCO₂ at mid-century are the two estimates using average climate sensitivity, a 3-percent discount rate, and the Nordhaus estimate of low-temperature damages.

8 Conclusions

We began by reviewing the U.S. government's estimate of the SCC, developed for use in cost-benefit analysis of regulatory proposals. We have ended with alternate estimates that are not just minor revisions to the published figure of \$21 per ton, but are higher, in most cases, by an order of magnitude or more. These estimates appear to be well outside the bounds of realistic short-term policy options, in the United States or elsewhere. How should these ultra-high SCC values be interpreted?

¹⁸ DICE uses an estimate of non-CO₂ forcings to capture the climate impacts of all greenhouse gases other than CO₂.

The SCC represents the marginal cost of climate damages, or the cost of doing nothing about climate change. In a cost-benefit framework, it should be compared to the marginal cost of climate protection. We have compared our SCC estimates to the marginal abatement cost on several versions of a maximum feasible abatement scenario, which would lead to zero or negative net global emissions before the end of this century. In the federal Working Group's analysis, the SCC is well below the abatement cost for these scenarios. We found that under many alternate sets of assumptions, the SCC is roughly equal to or greater than the cost of maximum feasible abatement. This remains true even when the SCC is re-estimated using a rapid-reduction emissions trajectory.

Once the SCC is high enough to justify maximum feasible abatement in cost-benefit terms, then cost-benefit analysis becomes functionally equivalent to a precautionary approach to carbon emissions. All that remains for economic analysis of climate policy is to determine the cost-minimizing strategy for eliminating emissions as quickly as possible. This occurs because the marginal damages from emissions have become so large; the uncertainties explored in our analysis, regarding damages and climate sensitivity, imply that the marginal damage curve could turn nearly vertical at some point, representing a catastrophic or discontinuous change.

The factors driving this result are uncertainties, not known facts. We cannot know in advance how large climate damages, or climate sensitivity, will turn out to be. The argument is analogous to the case for buying insurance: it is the prudent choice, not because we are sure that catastrophe will occur, but because we cannot be sufficiently sure that it will not occur. By the time we know what climate sensitivity and high-temperature damages turn out to be, it will be much too late to do anything about it. The analysis here demonstrates that plausible values for key uncertainties imply catastrophically large values of the SCC.

This result can be generalized to other environmental issues: when there is a credible risk that the marginal damage curve for an externality turns vertical at some threshold (representing discontinuous, extremely large damages), then the shadow price of the externality, such as the SCC, can become so large that cost-benefit analysis turns into cost-effectiveness analysis of the least-cost strategy for staying safely below the threshold.

Our results offer a new way to make sense of the puzzling finding by Martin Weitzman: his "dismal theorem" establishes that under certain assumptions, the

marginal benefit of emission reduction could literally be infinite (Weitzman 2009). The SCC, which measures the marginal benefit of emission reduction, is not an observable price in any actual market. Rather, it is a shadow price, deduced from an analysis of climate dynamics and economic impacts. Its only meaning is as a guide to welfare calculations; we can obtain a more accurate understanding of the welfare consequences of policy choices by incorporating that shadow price for emissions.

Once the shadow price is high enough so that maximum feasible abatement is a welfare improvement, there is no additional meaning to an even higher price. Doubling or tripling the SCC beyond that level would have exactly the same implications for market behavior and policy choices: it would still be optimal to eliminate emissions as rapidly as possible. In this sense, it bears some resemblance to infinity, which is unaffected by doubling or tripling.¹⁹ Our highest SCC estimates are clearly not infinite – but they may be close enough to infinity for all practical purposes.

What's left, finally, of the economic arguments for gradualism in climate policy, which seem to be endorsed by the Working Group's \$21/tCO₂ SCC? To support this approach, given our results, one would have to endorse the Working Group's view of most or all of the key assumptions and uncertainties explored in our analysis: the original DICE damage function, a discount rate of 3 percent, and average rather than 95th percentile climate sensitivity. Changes in these assumptions quickly push the SCC up into the \$150-\$500 range by midcentury, justifying the maximum feasible pace of abatement; changes in all of these assumptions yield an SCC well above that range. At such levels, cost-benefit analysis provides a result that is identical to a precautionary approach supporting immediate, large-scale action to reduce emissions and avoid dangerous levels of climate change.

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¹⁹ These SCC values bear an even closer resemblance to the concept of “machine infinity” in computer science, i.e. the largest number that a computer can represent. Doubling machine infinity cannot increase it (within that computer), but dividing by two decreases it. The same is true for the practical significance of an SCC estimate which is, for instance, 1.5 times the marginal cost of maximum feasible abatement.

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The Editor

Exhibit 18

Temperature impacts on economic growth warrant stringent mitigation policy

Frances C. Moore^{1,2*} and Delavane B. Diaz³

Integrated assessment models compare the costs of greenhouse gas mitigation with damages from climate change to evaluate the social welfare implications of climate policy proposals and inform optimal emissions reduction trajectories. However, these models have been criticized for lacking a strong empirical basis for their damage functions, which do little to alter assumptions of sustained gross domestic product (GDP) growth, even under extreme temperature scenarios^{1–3}. We implement empirical estimates of temperature effects on GDP growth rates in the DICE model through two pathways, total factor productivity growth and capital depreciation^{4,5}. This damage specification, even under optimistic adaptation assumptions, substantially slows GDP growth in poor regions but has more modest effects in rich countries. Optimal climate policy in this model stabilizes global temperature change below 2 °C by eliminating emissions in the near future and implies a social cost of carbon several times larger than previous estimates⁶. A sensitivity analysis shows that the magnitude of climate change impacts on economic growth, the rate of adaptation, and the dynamic interaction between damages and GDP are three critical uncertainties requiring further research. In particular, optimal mitigation rates are much lower if countries become less sensitive to climate change impacts as they develop, making this a major source of uncertainty and an important subject for future research.

Integrated assessment models (IAMs) have traditionally captured the negative impacts of climate change with a damage function that relates global temperature change to a loss of current economic output. This formulation captures the transient effects of climate on the economy such as lost agricultural output, increased cooling demand, or lower worker productivity due to hotter temperatures^{7–9}. Factors of production, namely labour and capital, and their total factor productivity (TFP) are not directly impacted, meaning that climate change has no effect, or only a very weak effect, on GDP growth. Two IAMs recently used for the US government social cost of carbon (SCC) estimate, FUND and PAGE, assume that GDP growth is entirely exogenous^{10,11}. In the DICE model, labour and TFP are specified exogenously and capital formation is determined through endogenous investment decisions⁵; temperature shocks can therefore alter economic growth through capital stock reductions, but this effect is small and indirect¹².

Damages from climate change that directly affect growth rates have the potential to markedly increase the SCC because each temperature shock has a persistent effect that permanently lowers GDP below what it would otherwise be (Supplementary Fig. 1). Continued warming therefore has a compounding effect over time, so that even very small growth effects result in much larger

Table 1 | Parameters used to calibrate the gro-DICE damage functions, reported in Dell *et al.* Table 3, column 4 (ref. 4).

	Effect 1 °C temp increase on GDP growth rates (γ_0)	Effect 1 °C temp increase on economic output (β_0)
Poor	–1.171 pp	–0.426%
Rich	–0.152 pp	0.371%

This specification includes 10 temperature lags and no precipitation controls. A brief summary of the estimation strategy used in ref. 4 is given in the Supplementary Information. pp: percentage point.

impacts than the traditional damage formulation¹². Examples of pathways by which temperature could affect the growth rate of GDP include damage to capital stocks from extreme events, reductions in TFP because of a change in the environment that investments were originally designed for, or slower growth in TFP because of the diversion of resources away from research and development and towards climate threats¹. Empirical evidence that these impacts exist is mounting. Two studies have found a reduced-form relationship between temperature shocks and GDP growth^{4,13}, and other studies have demonstrated plausible pathways including increasing conflict risk¹⁴ and changes in labour supply¹⁵. Previous work has demonstrated that DICE results are sensitive to the inclusion of growth impacts^{12,16}, but no previous studies have calibrated these damages using empirically grounded results from the econometrics literature. Given the potentially first-order impacts of these growth effects, understanding their implications for climate policy is of critical importance.

Here we examine alternative formulations of the DICE damage function based on empirical estimates of the impact of inter-annual temperature variability on national economic output and growth rates by Dell and colleagues⁴. They find large, statistically significant negative effects of hot temperatures on growth rates in poor countries, smaller effects in rich countries, and mixed effects on output (Table 1). To implement these parameters in an IAM, we develop a two-region version of DICE (ref. 17; DICE-2R). We then modify the damage pathway so that warming affects either TFP growth or capital depreciation as per results in ref. 4 (gro-DICE) and investigate sensitivities to the parameters used by Dell *et al.*⁴ (Methods). We present results of the TFP pathway here, but the capital pathway gives quantitatively similar results and is discussed further in the Methods and Supplementary Information.

As Dell *et al.*⁴ use transient and largely unanticipated weather shocks in their estimation, the growth-rate sensitivities (reduction

¹Emmett Interdisciplinary Program in Environment and Resources, Stanford University, California 94305, USA. ²Center on Food Security and Environment, Stanford University, California 94305, USA. ³Department of Management Science and Engineering, Stanford University, California 94305, USA.

*e-mail: fcmoore@stanford.edu

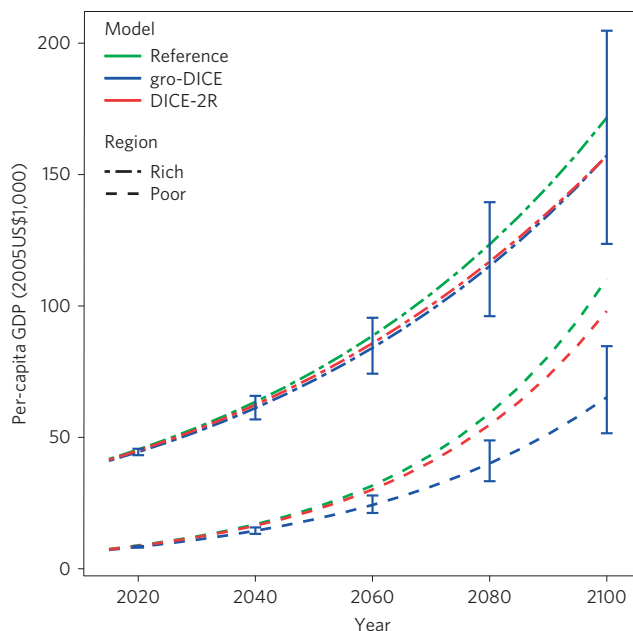


Figure 1 | Per-capita GDP for rich and poor regions for the reference (no damages) run and DICE-2R and gro-DICE models under business-as-usual. Temperature in the reference reaches 5 °C above pre-industrial by 2100. The error bars show results using $\pm$ one standard error (68% confidence interval) around the growth-rate damages reported in ref. 4 (Table 1).

in growth rate from 1 °C of warming) shown in Table 1 are the short-run impacts of higher temperatures. Long-run impacts of the permanent warming associated with climate change could be either larger (owing to intensification) or smaller (owing to adaptation) than this short-run effect⁹, although several studies show evidence for some adaptation^{18–20}. We adopt optimistic adaptation assumptions in gro-DICE by assuming that the long-run effect of temperature on GDP growth is zero and that the short-run impacts decay exponentially at a constant adaptation rate (Methods). As there is a very limited empirical basis for the rate of adaptation, we assume a value of 10% per year and examine sensitivity to this parameter (Supplementary Fig. 2).

Figure 1 shows the trajectory of per-capita GDP under business-as-usual for the reference (no climate damages), DICE-2R and gro-DICE models. Temperatures exceed 4.5 °C by 2100, causing economic losses in both models with damages. Impacts in DICE-2R are modest because impacts are transient and offset by sustained growth in TFP, labour and capital: the difference from reference GDP is less than 12% in both poor and rich regions by 2100. In contrast, the growth effects in gro-DICE compound over the century, leading to much larger impacts. The average annual growth rate in poor regions is cut from 3.2% to 2.6%, which means that by 2100 per-capita GDP is 40% below reference. The much smaller growth effects in rich countries, combined with the fact that warming slightly improves economic output, means the gro-DICE and DICE-2R timepaths are very similar in the rich region. Figure 1 also shows the effect of increasing and decreasing the growth-rate sensitivity parameter by one standard error. The large negative impact in poor countries is robust, but uncertainty around the magnitude of growth impacts in rich regions means that they could benefit from warming.

Figure 2 shows results if mitigation levels are chosen to maximize global discounted social welfare. Optimal climate policy in DICE-2R demonstrates a classic ‘policy-ramp’ in which mitigation efforts increase gradually over the century, with emissions peaking in

2060 and warming of over 3.5 °C by 2100. In contrast, optimal mitigation in gro-DICE consists of eliminating emissions in the very near future to stabilize global temperatures below 2 °C above pre-industrial. Even optimistic assumptions about temperature effects on GDP growth (the upper bound on the error bars in Fig. 2) lead to more stringent near-term mitigation than DICE-2R and elimination of emissions by 2070. The findings of near-term decarbonization and global temperature stabilization below 2 °C are robust to changes in the adaptation rate, which we vary between 0 and 20% per year (Supplementary Fig. 3). A variant of gro-DICE in which temperatures affect the depreciation of capital rather than TFP growth also gives quantitatively similar results (Supplementary Fig. 4).

The motivation for rapid decarbonization can be illustrated with the high SCC in gro-DICE (Fig. 2). One additional ton of CO₂ emitted in 2015 reduces net social welfare by US\$33 in DICE-2R but by US\$220 in gro-DICE. This value is higher both because climate damages are larger in gro-DICE and because slower economic growth leads to a lower discount rate⁵. The trajectory of the SCC over time has an inverted U-shape determined by relative changes in the marginal utility of emissions and the marginal utility of consumption over time (Supplementary Fig. 5). The additional mitigation undertaken in the gro-DICE optimal run does reduce damages compared to business-as-usual, but poor countries still suffer substantial impacts, with per-capita GDP in 2100 still 20% lower than the reference.

Our results thus far assume a static damage function, but the relationship between economic growth and temperature is likely to change over time. Dell *et al.*⁴ find much higher sensitivity of GDP growth rates to warming in poor countries than in rich (Table 1), which could result from two possible mechanisms. One is that high sensitivity may result from biophysical temperature thresholds, beyond which warming becomes particularly damaging^{8,21}. As poor countries are, on average, hotter than rich countries, they are exposed more frequently to damaging temperatures and therefore show higher sensitivity to temperature. Under this mechanism, the sensitivity of rich countries would increase as they warm. Alternatively, higher temperatures may be more damaging in poor countries because their economies are reliant on climate-exposed sectors such as agriculture and natural resource extraction, or because risk management options such as insurance or air conditioning are not as widely available. In this case we would expect the sensitivity of poor regions to warming to decrease as per-capita GDP increases. We call these two mechanisms the ‘temperature’ and ‘resilience’ mechanism respectively and implement each separately in gro-DICE by making the growth-rate damage parameters a function of either temperature change or per-capita GDP (Methods).

Although both the temperature and resilience mechanisms could explain the different sensitivities of rich and poor countries to higher temperatures observed today, they have contrasting implications for how damages might evolve over time and for optimal climate policy (Fig. 3). As mitigation is already so high in the standard gro-DICE model, adding the temperature mechanism has little additional effect. However, the resilience mechanism results in a very different mitigation trajectory. Early mitigation serves to slow the rate of climate change but is later relaxed because of the benefits of economic growth in poor regions in terms of reduced sensitivity to warming (Supplementary Fig. 6). Once sensitivity in poor regions stabilizes in 2070 at the level observed at present in rich countries, mitigation gradually increases so that emissions peak in 2120 and are eliminated by 2150, stabilizing global temperatures at 6 °C above pre-industrial. The evolution of the damage function over time therefore has important policy implications for balancing the dual priorities of increasing resilience through economic growth and decarbonization.

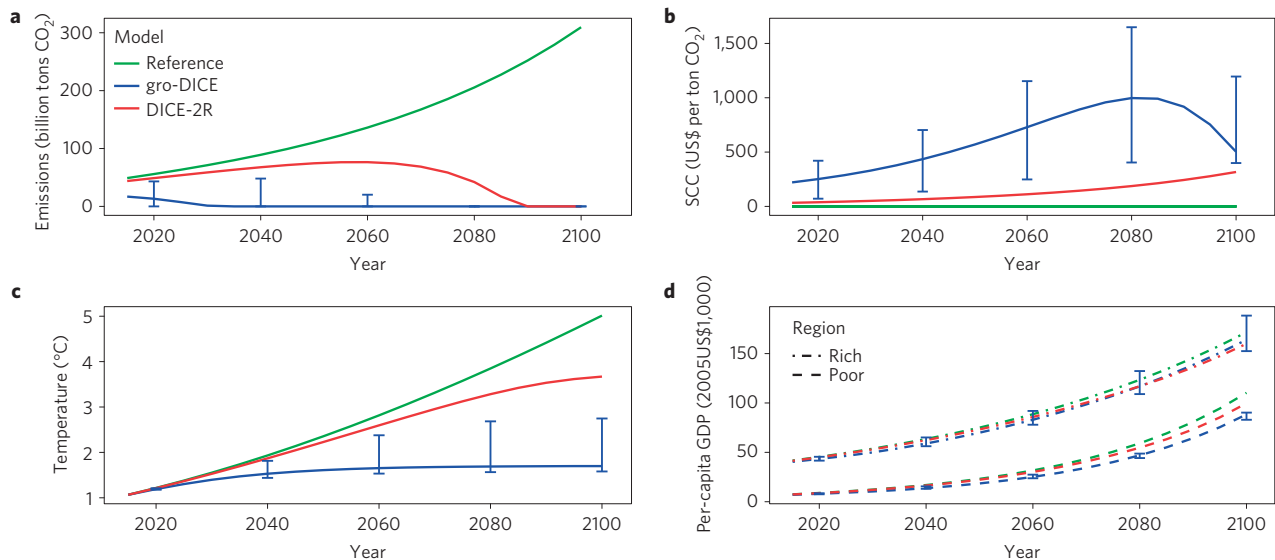


Figure 2 | Results of Pareto optimal runs of DICE-2R and gro-DICE. a–d, Annual global emissions (a), SCC (b), global temperature (c) and regional per-capita GDP (d). The error bars show results from Pareto optimal runs of gro-DICE using $\pm$ one standard error (68% confidence interval) around the growth-rate sensitivity reported in ref. 4. The reference is defined as a model run with no climate damages and therefore has zero SCC by definition.

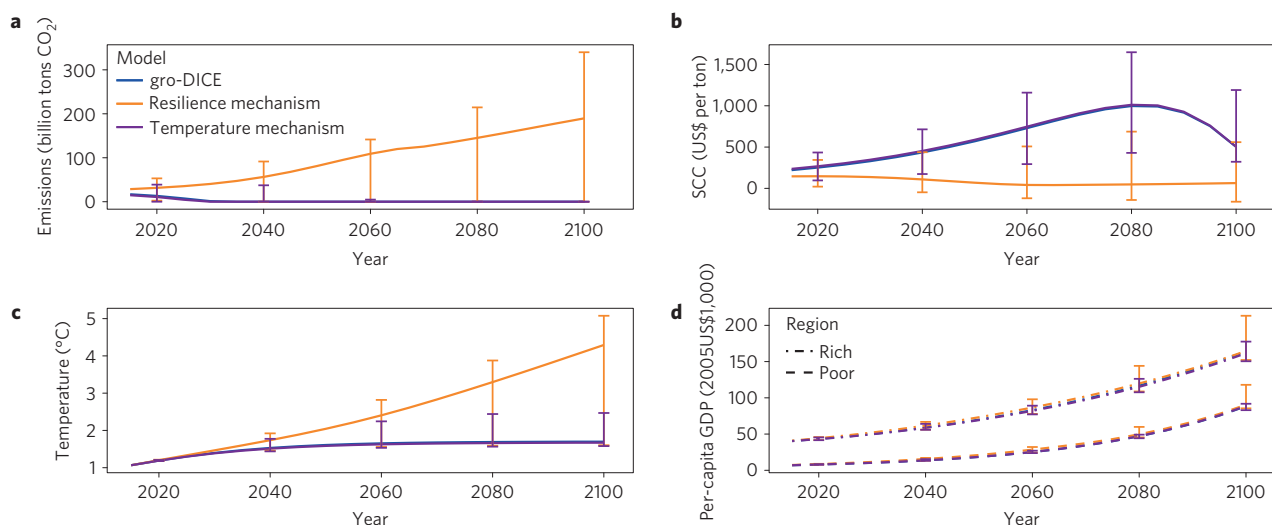


Figure 3 | Results of Pareto optimal runs of gro-DICE, and versions of gro-DICE that include dynamic damage functions based on either the temperature or resilience mechanisms (Methods). a–d, Annual global emissions (a), SCC (b), global temperature (c) and regional per-capita GDP (d). The gro-DICE and temperature mechanism lines are indistinguishable. The error bars show Pareto optimal runs using $\pm$ one standard error (68% confidence interval) around the growth-rate sensitivity reported in ref. 4.

One limitation of the DICE model is the simplicity of the reduced-form mitigation function^{5,22}. First, the mitigation level can fluctuate freely, with no expansion constraint from period to period. This fails to capture real-world inertia, represented in other energy system IAMs, which limits the rate of decarbonization owing to delayed availability of low-emitting technologies, construction lead times, stranded assets, or other capital turnover factors^{23,24}. Second, the simple mitigation cost function constitutes a claim on current output without affecting the factors of production or TFP. Mitigation at the rate implied by gro-DICE could well impose its own persistent impacts on economic growth, as suggested by some previous research²⁵. Although gro-DICE was designed to investigate the effects of temperature on growth, it does not include the converse effect of mitigation, something beyond the scope of this paper but a priority for future research. For both these reasons, the results regarding very rapid, near-term mitigation should not be

over-interpreted as evidence that such a policy would necessarily be economically optimal. Nevertheless, the findings that temperature effects on growth rates imply much larger climate damages and, correspondingly, more stringent mitigation than is justified by transient impacts on economic output are probably robust to more realistic modelling of mitigation costs.

Historically, attention has narrowly focused on climate sensitivity and the discount rate in driving uncertainty in IAM results^{26,27}. We compare these two uncertainties with the new factors introduced in this paper. Figure 4 shows that the magnitude of GDP growth-rate sensitivity, the rate of adaptation, and how sensitivity to warming changes with per-capita GDP are at least as important as climate sensitivity and the pure rate of time preference in determining optimal climate policy over the next century.

This paper has shown that allowing climate change to directly affect economic growth through impacts to TFP or capital can

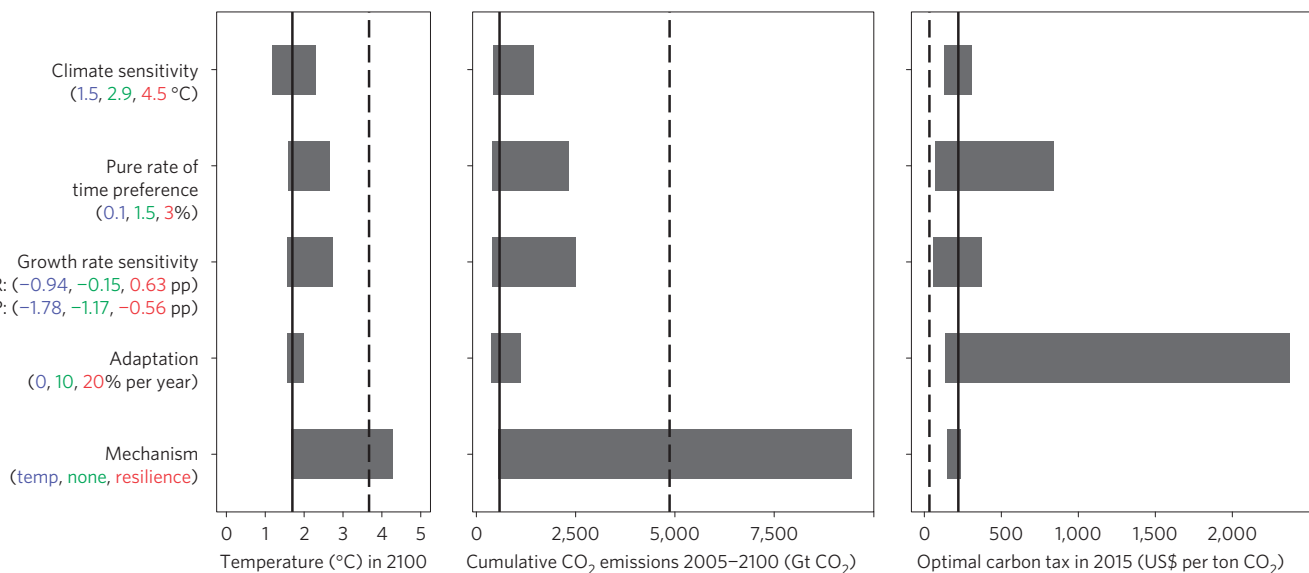


Figure 4 | Sensitivity of three key indicators of twenty-first century climate policy to climate sensitivity, the pure rate of time preference (PRTP), the sensitivity of economic growth rates to temperature, adaptation rate, and the temperature or resilience mechanisms. The lower, main and upper values of the parameter range are labelled in blue, green and red, respectively. The climate sensitivity range is derived from the 66% confidence (likely) interval given by the Intergovernmental Panel on Climate Change Fifth Assessment Report³⁰. The values for the pure rate of time preference do not correspond to a confidence interval, but to noted low and high values from the literature. The growth-rate sensitivities are based on $\pm$ one standard error (68% confidence interval) as reported in ref. 4. Results for the gro-DICE model (solid line) and DICE-2R model (dashed line) are shown for comparison.

significantly increase the SCC and the optimal rate of near-term mitigation. This finding holds for empirically derived estimates of the magnitude of temperature effects on growth rates using optimistic adaptation assumptions, and is robust to uncertainty in the sensitivity parameter and the rate of adaptation, but not to the mechanism driving different growth-rate impacts in rich and poor regions. Although the simplified representation of mitigation in DICE means the optimal level of near-term mitigation may be overestimated here, the higher marginal damage of CO₂ emissions should be robust to higher mitigation costs. The sensitive dependence of model results on the magnitude of growth-rate impacts, the adaptation rate, and the interaction of temperature sensitivity with per-capita GDP indicate that these topics should be a priority for future empirical work. If further studies confirm that climate change has the potential to adversely affect TFP, capital stocks or labour supply then aggressive, near-term mitigation could well be warranted.

Methods

To study the growth effects as presented in Dell *et al.*⁴ (DJO in this section) we created a two-region version of DICE (DICE-2R). The rich and poor regions are parameterized on the basis of output-weighted regional values from the 2010 RICE model^{5,17} (Supplementary Table 1). DICE-2R chooses mitigation and savings so as to maximize the discounted sum of utility in both regions, weighted by regional Negishi weights²⁸. We also altered DICE by fixing emissions in 2005 and 2010, making 2015 the first year when mitigation is possible. As the parameterization of the rich and poor regions in DICE-2R, although consistent with RICE2010, differs from the DICE-2013R aggregate, DICE-2R does not exactly reproduce the most recent DICE results⁵. Specifically, the slightly faster TFP growth in DICE-2R means that incomes and emissions are higher in DICE-2R than in DICE-2013R in the second half of the twenty-first century.

We investigate two alternative pathways by which warming could affect economic growth: slowing the growth of TFP or accelerating depreciation of the capital stock. For the first pathway, climate damages impact the growth rate of TFP, reflecting the fact that climate change could affect the productivity of the research sector or existing investments¹²:

$$A_{j,t} = (1 + j_{\text{TFP},t} - r_{\text{DJO},t})^{\Delta t} A_{j,t-1} \quad (1)$$

$$j_{\text{DJO},t} = \tilde{\gamma}_0 T_t$$

where $A_{j,t}$ is TFP in region j in time period t , j_{TFP} is the exogenous annual TFP growth rate, T is the global temperature change from pre-industrial, Δt is the model time step, and $\tilde{\gamma}_0$ is the regional growth-rate sensitivity to temperature, calibrated to reproduce the DJO result (Table 1). Calibration is necessary because economic growth is not completely exogenous in DICE but is partly determined by an endogenous capital stock, meaning that reductions in TFP affect economic growth both through lower productivity and through lower capital. Details on the calibration are given in the Supplementary Information. The gro-DICE model also includes transient impacts of temperature on regional output estimated by DJO ($\beta_0 T_t$, Table 1), but this effect is small compared with the growth-rate damages.

The second pathway assumes climate damages fall on the capital depreciation rate. This simulates the impact of climate change on physical infrastructure through more frequent or larger extreme events or on institutional capital through, for example, increased risk of civil conflict¹⁴. We calibrate the relationship between temperature change and depreciation rate for the DJO results for values of capital stock, investment, TFP and labour in the reference run for a range of temperatures up to 6 °C (calibration details in Supplementary Information and Supplementary Fig. 9). This gives a concave, quadratic function relating warming and depreciation rate (Supplementary Fig. 10). We find comparable implications for climate policy along both the TFP and depreciation pathways. In reality, both impact pathways (as well as others) are likely to be important in determining climate change damages, but we present them separately here for clarity and because of the lack of empirical studies on their relative roles.

We model adaptation in gro-DICE using an exponential decay curve in which the initial impact of a change in temperature (determined by parameters calibrated to the DJO results) declines over time at the rate of adaptation. We introduce a new variable, the effective temperature, which is the sum of all residual temperature shocks:

$$ET_t = \sum_{i=1850}^t (T_i - T_{i-1}) e^{-a(t-i)}$$

where ET_t is the effective temperature at time t , T_i is the temperature in year i , and a is the rate of adaptation. For runs with a positive adaptation rate, ET_t replaces T_t in the calculation of damages (equation (1)). As there is a very limited empirical basis for the rate of adaptation, we use a value of 10% per year and vary it between 0 and 20% per year in a robustness check. Ten per cent per year is equivalent to a 95% reduction in the impact of a temperature shock after a 30-year adjustment period (Supplementary Fig. 2). The contribution to effective temperature of temperature change before the start of the model time horizon is based on the global surface temperature record since 1850 (ref. 29). The effective

temperature rather than absolute temperature is then used to define damages on output and TFP or capital. This formulation means that impacts depend both on the magnitude and the rate of temperature change because faster warming results in larger disequilibrium and therefore higher adjustment costs.

The temperature and resilience mechanisms are implemented such that the growth-rate damage parameters $\tilde{\gamma}_0$ are a function of either temperature or per-capita GDP, respectively. In the temperature mechanism, sensitivity in poor regions remains constant but increases with warming in rich regions, not exceeding the sensitivity observed at present in poor regions (Supplementary Fig. 11). The resilience mechanism causes sensitivity in poor regions to decrease until they reach the per-capita GDP of rich regions today, reducing damages from warming over time as poor regions develop (Supplementary Fig. 12).

The effect of parametric uncertainty in five factors is investigated by independently varying each parameter from its reference value to a high or low value using one-at-a-time sensitivity analysis (Fig. 4). The uncertainties captured and not captured by this approach are discussed more fully in the Supplementary Information.

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Author contributions

F.C.M. and D.B.D. designed the analysis. D.B.D. performed the analysis. F.C.M. and D.B.D. analysed results and wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.C.M.

Competing financial interests

The authors declare no competing financial interests.

Exhibit 19

Cultural Resources Survey Assessment of Colstrip Alternative Route for the proposed Tongue River Railroad

Prepared by: Chris Finley, Retired National Park Service Archaeologist for Bighorn Canyon National Recreation Area

Results of an inventory to evaluate the quality of the Tongue River Railroad Cultural Resource Survey conducted by ICF International, the third party contractor hired to complete the Section 106 process, in 2013 and 2014 on the Tongue River Railroad Colstrip Alternative for the Surface Transportation Board.

Background:

At the request of the Sierra Club and the Colstrip Alternative Landowners group, I visited the Tongue River Railroad Colstrip Alternative project area in 2014 and observed the ICF Cultural Resource Reconnaissance Survey while it was underway. When the collected documentation was released to the individual land owners I received copies of all site forms and support documentation for review from Carrie La Seur the Attorney representing the land owners association. After reviewing the documents it was apparent that the documentation did not follow guidelines and standards provided in the MTSHPO planning bulletin, and was incomplete, inaccurate, and misleading in providing information for determining potential eligibility of the sites for the NRHP. My concerns include:

1. Montana SHPO standard (CRIS) site forms include 5 sections listed below;
 - (A). Location information.
 - (B). Environmental information.
 - (C). Assessment, recording and management documentation.
 - (D). Prehistoric site description.
 - (E). Historic site description.

Only minimal information was provided on section A, D, or E, and section B and C were totally ignored, and information for section D and E were consolidated into a single paragraph.

2. Montana SHPO standard (CRIS) forms also include a separate form to document isolated finds (IF) which very rarely warrant Smithsonian site numbers. The standard isolated find form was not used, and the same format was used by ICF to document sites and isolates.
3. Only three of the site forms provided to landowners had the correct Township/range information.
4. None of the site forms provided to the landowners had the correct UTM Coordinates.
5. There was no environmental information included (specifically surface visibility).
6. There was no information or assessment of eligibility.
7. There were no site maps or illustrations of features.
8. Identification/description of artifacts and features were incorrect.

I was also invited to attend a landowners meeting and it was clear that ICF had not followed guidelines and standards provided in National Register Bulletin #24 pertaining to the importance of gathering information from local ranchers whose families, in some cases, have

occupied the area since the early 1880's. The general consensus of the landowners was that any information they offered was totally ignored by the ICF crew leaders and that opinion was confirmed by the documentation they received from STB after the field work was finished.

In discussions with some of the Tribal Representatives who participated in the surveys the general consensus was that as a result of heavy vegetation cover ground visibility was so poor they felt like they were wasting their time and just going through the motion of conducting a valid survey. They also felt that some information offered to the ICF crew leaders was ignored and downplayed, and this opinion was clearly confirmed in the information included in the site forms provided to MTSHPO by STB.

I also spent time looking at 3 private stone artifact collections from the area and was not surprised to observe that each collection included Paleoindian Projectile Points including examples of Agate Basin, Hell Gap, and Cody Complex, and included Pryor Stem and Jimmy Allen Terminal Paleoindian Projectile Points as well. The majority of points (approximately 75%) from each collection contained examples of Early, Middle and Late Archaic Northwest Plains Projectile Points, and there were a few examples of Late Plains Prehistoric-Early Plains Historic points as well. This information confirmed my expectations that the project area was typical of prehistoric land use utilization throughout the western Plains and foothills of the Rocky Mountains for over 10,000 years, and that significant cultural sites could be discovered during future intensive survey, site testing and data recovery efforts if significant sites could not be avoided, and the project was approved for construction.

After discussing my opinion of the quality of the "Good Faith Effort" by ICF and STB to meet Section 106 obligations the Sierra Club and the Colstrip Alternative Land Owners Group agreed that a field assessment of the ICF reconnaissance survey was in order. The decision was made to spend eight days in the field with my crew looking at a sample of the sites documented by ICF, and to check the accuracy of their documentation and how complete the results of the survey coverage was.

Methodology;

My crew consisted of myself and three members of the Crow and Northern Cheyenne Tribe who have worked extensively with me in the field for several years. Crew members included Hubert B Two Leggings (former Crow Tribal Cultural Director and THPO) who has worked with me for six years, Johnny Tim Yellowtail (former Crow Tribal Cultural Staff member) who has worked with me for five years, and Serina Red Robe (from the Northern Cheyenne Otter Creek Descendants) who has worked with me for four years.

Field work took place between April 12 and April 19, 2015 to take advantage of ground visibility conditions before seasonal vegetation growth would limit ground visibility. The goal of the field work was to locate and evaluate some of the sites documented on private land by ICF during the 2014 field season, determine how complete the survey

coverage was and to visit sites ICF had missed or ignored within the project area considered important to the landowners.

Before field work commenced, a meeting took place with the Northern Cheyenne THPO James Walks Along and my crew to discuss the information submitted to MTSHPD by ICF and what his suggestions and concerns were about the field work we were about to conduct. He will receive a copy of this report, and will have input on how TCP and NAGPRA issues will be addressed.

Results:

Seven separate areas surveyed by ICF during the 2014 field reconnaissance survey were selected for further investigation during the course of the planned 2015 field assessment. A total of 20 previously documented sites were examined in six of these survey areas, and the seventh area is in an area where the ICF crew leader informed the land owners that there were no cultural resources observed on their property.

Area #1: This area is located on land owned by Hugh and Ann Wells, and we examined TR-F-18 and TR-F-19, documented in 2014 by ICF.

TR-F-18: This site was documented as a low density lithic scatter located 15m north of a large sandstone outcrop. The site was plotted on the 7.5' Quad map near the large sandstone outcrop, but the UTM coordinates entered into the site form place the site place 3/8 of a mile east and south of the above mentioned sandstone outcrop. We went to the UTM location listed on the site form and the location did not match the site description on the form. An intense survey of the location led to the conclusion that there were no cultural materials at this location.



Site overview looking east at UTM location of site given on site form.



GPS unit at UTM location given on site shown above (note zone 13 on the GPS).

TR-F-19: There was no problem with this site except ground visibility around the feature was 0%.

Newly discovered sites:

Six undocumented sites and one isolate were discovered in this area including one lithic scatter (A), one isolate consisting of a complete stone knife (B), two rock art sites (C & E), one rock shelter with lithics present (D), one lithic procurement site (L), and one prehistoric burial site. More details on these sites will be discussed in detail in a separate section of this report.

Area #2: This area is located on land owned by the Rocker Six Cattle Company.

TR-F-4: This site is listed as one-tier rock carin constructed of 20 cobbles. During the survey conducted in 2014 this site was identified as a probable burial site by James Walks Along who left a Tobacco offering on the site. Hubert Two Leggings witnessed this event. Apparently the ICF crew leader chose to ignore this information. During our investigation we collected more detailed information and agree with James Walks Along and Hubert Two Leggings that this site should be treated as a potential burial site. Ground visibility was 0% as a result of heavy vegetation cover.

TR-F-05: This site is listed as a “gravel borrow pit” and “appears to be of historic age and associated with gravel extraction activities, possibly for the construction of nearby roads”. There is a well defined road (see photo) entering the pit area from the northeast that was not documented during the 2014 ICF survey. An interview with the land owner would have revealed that the gravel pit and access road was established by the county road department for construction of the existing county road.



County access road to the gravel borrow pit looking northeast.

TR-F-06: This site was listed and described as a one-tier rock cairn. The rocks actually form a half circle (stone alignment) 3.1m X 2.8m with the opening facing northeast. Rock size ranged from 15cm to 30cm, and ground visibility was less than 20% as a result of heavy vegetation cover. The feature was probably used to set up part of a Tipi as a shade shelter during food or hide processing tasks according to Hubert Two Leggins (see photo).



Outline of the half stone circle documented by ICF as a cairn on TR-F-06.

TR-F-07: No problem with this site, and ground visibility was approximately 50%.

Newly discovered sites:

Six undocumented sites or components of ICF sites and one isolate were discovered in this area including the county access road (M) to the gravel borrow pit (TR-F-05), two rock cairn sites (O & AC), two historic structure sites (AB-1 & AB-2), one probable burial site, and one isolate consisting of a single large primary flake exposed on a gopher mound. The above mentioned historic structure was plotted incorrectly (approximately 400m north of its actual location) on the project map, and no site forms were provided for this site, or the historic ranch buildings located directly east of the road in the same area.

Area # 3: This area is located on land owned by the Rocker Six Cattle Company.

TR-E-I-25: No problem with this site.

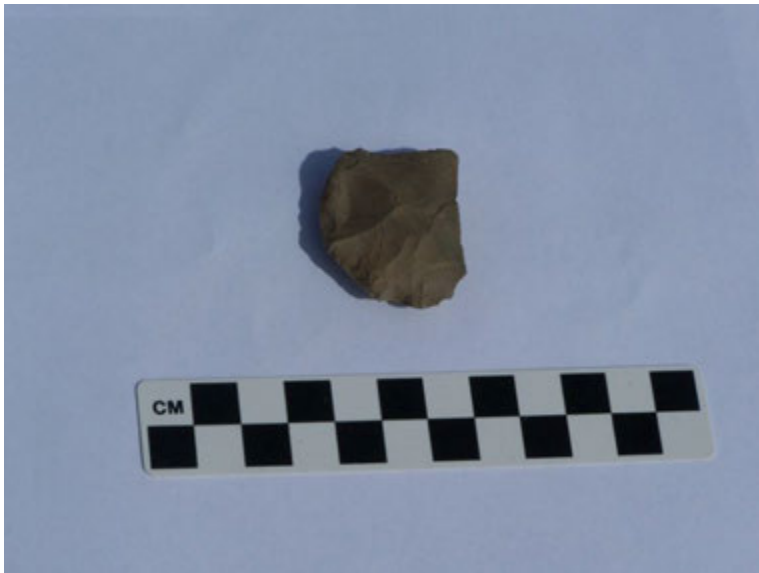
TR-E-I-27: This site was listed as an isolate with one biface and one secondary stage reduction flake present. During our investigation of the site we found the “biface” (which turned out to be a fragment of a biface) and the secondary stage reduction flake plus an additional 9 flakes, two cores and one additional biface fragment (see photos). This site is not an isolate but a lithic scatter.



Site overview looking east.



Cores found on site.



Biface fragment found on site.

TR-E-63: This site was listed as a one-tier rock cairn and a rock alignment. The “circular cairn” measured 1.5m in diameter. The rock alignment consisted of 15 local sandstone cobbles in a semi-circular format with a diameter of 1.5m. These features are located within 25m of a large cluster of stone circles left undocumented during the ICF 2014 survey, and are most likely hearths. Eight stone circles each with a well defined internal hearth were documented on this site (H), and several of the internal hearths associated with the stone circles are similar to the two features documented during the 2014 ICF survey, and fall within the same size range.

TR-E-65: This site was listed as a poorly defined and abandoned two track dirt road, and is shown on the 7.5' Quad map as being approximately 1000 feet long. This is not a poorly defined two track road, but is an abandoned section of the county road. The

feature is well defined with a flat road bed with borrow pits on both sides for the entire length, and ties back into the existing county road ½ mile north of where it leaves the existing county road as indicated on the 7.5' Quad map included with the site form. There is also a well defined irrigation ditch (undocumented by ICF in 2014) that courses along the west side of this road on the north ½ of the abandoned county road segment (also undocumented by ICF in 2014).



View of abandoned county road looking northeast where it leaves the existing county road.



View of abandoned county road looking south near where it ties into the existing county road on the north end.

Newly discovered sites:

Five undocumented sites or components of ICF sites were discovered in this area including the northern segment of the abandoned county road ((TR-E-65) one lithic

scatter (F), one isolate consisting of 3 secondary flakes (G), one stone circle site (H), and one abandoned historic irrigation ditch (I).

Area # 4: Located on land owned by the Rocker Six Cattle Company.

TR-E-44: This site is listed as four one-tier stone circles (tipi rings) constructed from large local sandstone and scoria cobbles. All of the members of my crew agree with me that this is not a stone circle site. The rocks were loose on the surface, and there was no evidence of sodding or lichen deposits. Also, the rocks were too small (10cm to 15cm) to weight down a tipi. Average rock size on Stone Circle site H located approximately 2 miles north of this site was 20cm to 30cm, and the rocks were heavily sodded in, and had well developed lichen deposits on the rocks, or TR-E-45 just west of this site that was described as a possible effigy that was actually a cluster of 4 Tipi rings complete with internal hearths, with rock size averaging >30cm in size with the rocks heavily sodded and with well established lichen deposits. The land owner also informed us that approximately 1000 head of cattle are trailed back and forth through this site in the spring and fall resulting in a constant rearrangement of the loose surface rocks. This site was also plotted on the west side of the county road on the 7.5' quad map provided with the site form. The site is actually located on the east side of the road as indicated by the UTM coordinates and site photos included in the site form (see photo).



Rock from the supposed tipi ring on the site.

TR-E-45: This site was described as a stone alignment, “possible effigy” constructed of local sandstone and scoria cobbles and boulders. The “possible effigy” was actually a cluster of 4 Tipi rings complete with internal hearths, with rock size averaging >30cm in size with the rocks heavily sodded with well-established lichen deposits (see photos).



Stone circle #1 on the left, and stone circle #2 on the right.

TR-E-46: This site is listed as a “gravel borrow pit” and “appears to be of historic age and associated with gravel extraction activities, possibly for the construction of nearby roads”. An interview with the land owner would have revealed that the gravel pit and access road was established by the Rosebud County Road Department for construction of the existing county road.

TR-E-47: This site was described as seven small shallow depressions that were used for prehistoric and / or historic warfare and/or hunting. Three of these shallow depressions on the flat area on the south end of the “site” are probably there as a result of the installation of the power line located just south of this area to provide water for a well just north of the Rocker Six Corrals documented as TR_F-BO45. It was common practice to park the auger truck for the night and run the auger into the ground to secure the boom and avoid damage during high wind episodes. The land owner remembers the vehicle parking there during installation of the power line (see photo of Hubert Two Leggings on his knees in one of these depressions). The other four depressions are in different stages of sod restoration as is clearly illustrated in site photos of feature 1 and feature 2 (where the edges of the disturbance have not even slumped in yet in feature2). These depressions are not depressions that were used for warfare or hunting blinds, but are simply the result of depressions (i.e., bull wallows) caused by bulls rooting and throwing/pawing dirt over their backs with their front legs during mating/fighting or to protect themselves from biting insects (face flies, horse flies, etc). There was a fresh example of this disturbance documented and photographed on TR-E-I-15 recorded as an isolated find by ICF in 2014 (see photo). My crew agreed with me that these features are

not associated with prehistoric and/or historic warfare and/or hunting, and should not be included in this project as cultural resources.



Burdick Two Leggins on his knees in one of the auger holes.



Fresh “Bull Wallow” from last fall measuring 1.2m X 1.4m in diameter, and 20cm deep.

TR-E-56: This site was described as “a petroglyph of undetermined age”. This petroglyph is the letter “N” etched into the rock face. Segments of the etching show no evidence of weathering, and 1/3 of the etching looks like it could have been done within the last few years. There is no date associated with this etching, and in my opinion it is not over 50 years old, and therefore should not be documented as a historic property.

Newly discovered sites:

There was one undocumented lithic scatter discovered in this area (AD) during our survey.

AREA #5: This area is on land owned by the Rocked Six Cattle Company.

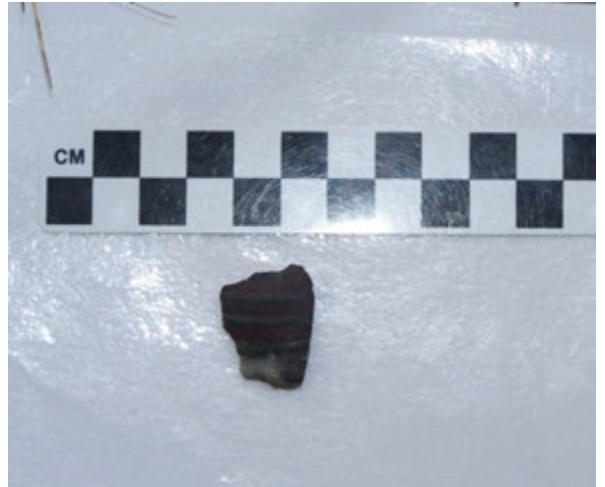
TR-E-I-15: This site was documented by ICF as an “Isolate” with three flakes and one fragment of shatter. Our survey revealed a large lithic scatter at this location with approximately 100 porcellanite flakes 2cm to 5cm in size (mostly secondary and tertiary), three tertiary non-volcanic glass flakes and the midsection of a gray porcellanite projectile point 23mm long, 17mm wide, and 4mm thick (probably Late Prehistoric). There was also evidence of final stage reduction micro-flakes included in the majority of gopher mounds scattered across the site indicating subsurface deposition of cultural material. Ground visibility was estimated at 10% to 40% over the majority of the site with the exception of a slump area on the east side of the site where the projectile point fragment and several flakes were exposed. The site was 40m long on a north/south axis, and 10m wide on an east/west axis. There was also a bull wallow on this site that was most likely made last fall, and was photographed to provide a fresh example of the bull wallows described as “pits described by ICF as possibly used for prehistoric and/or historic warfare and/or hunting” by ICF on TR-E-47 (photo will be included in both sections of this report). The bull wallow was 1.2m X 1.4m in diameter, and 20cm deep.



Site overview looking southeast.



**Gray Porcellanite projectile point midsection.
flake.**



**Non-volcanic glass tertiary
flake.**



**Fresh "Bull Wallow" from last fall measuring 1.2m X 1.4m in diameter and 20cm
deep.**

TR-E-26: This site was documented as a “low density” lithic scatter with 10 flakes present. During our survey we documented 18 flakes, 1 large gray porcellanite core, and 1 gray porcellanite scraper 58mm long, 31mm wide, and 7mm thick.



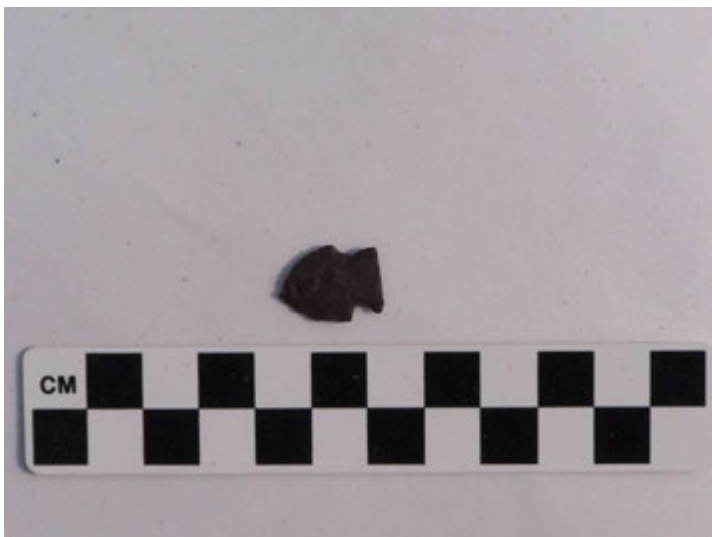
Scraper found on site.

TR-E-27: This site was documented as a “low density lithic scatter, and all we found different from their documentation was the presence of a gray porcellanite core.

TR-E-28: This site was documented as a low density lithic scatter. There was no problem with this assessment except we found a stage 4 gray Porcellanite biface fragment 45mm long, 17mm wide, and 6mm thick, and a complete Late Prehistoric side notch projectile point 18mm long, 12mm wide, and 3mm thick on this site (see photos).



Gray Porcellanite Biface fragment.



Dark purple Porcellanite side notch projectile point (Late Prehistoric).

TR-E-29: This site was not included on the project map.

Newly discovered sites:

There were 2 undocumented isolated finds and one undocumented lithic scatter found in this area during our survey. One isolate consisted of a gray Porcellanite retouched flake (AH), and the other isolate was a red Porcellanite scraper (AE). The lithic scatter (AG) consisted of 11 red and gray Porcellanite flakes, 1 red Porcellanite core, and the distal end of a gray Porcellanite projectile point fragment

21mm long, 15mm wide, and 3mm thick (probably Late Prehistoric). All but two of the artifacts documented were found in a blowout area on the north side of a large sandstone boulder indicating the possibility of buried cultural material on the site. Ground visibility around the blowout area was less than 10%.

Area #6: This area is on land owned by the Rocker Six Cattle Company.

TR-E-14: This site was documented as a “low density lithic scatter” consisting of 100-200 flakes. That many flakes on this site should not be considered low density. The only place ground visibility on this site is 100% is in the two track road passing through the site. Some areas of the site have approximately 20% ground visibility, but ground visibility on the majority of the site and the surrounding area is 0% due to heavy ground cover vegetation (see photos attached to site form for an example).

Newly discovered sites:

There was one probable burial site and one stone circle site (AF) discovered in this area.

Area #7: This area is on lands owned by Hank Coffin and Kirk Green. Hank Coffin (a Crow Tribal Member) was informed that no cultural resources were found on his land even when he offered to show the ICF crew leader sites he knew were there. Kirk Green tried to show the ICF crew leader a “Box Burial” and was told that “they (ICF) did not know what a Box Burial was and would not deal with it”.

Newly discovered sites:

On Hank Coffin’s property we documented 9 sites including two burial sites documented as 1 probable cairn burial that could be either prehistoric or historic in origin, and 1 historic burial (a family member of Hank Coffin) with documentation. We also recorded 1 TCP with documentation, 3 lithic scatters (S,V, & X) 1 lithic procurement site (W), 1 cairn, and 1 historic site that was reported to be an historic military artillery emplacement(U).

On Kirk Green’s land we documented 2 sites including 1 crevice burial and 1 Box burial which contained a hand made coffin made sometime between 1888 and 1900.

There are ten site forms that warrant comment that contain errors in site identification/evaluation, or artifact identification, and comments related to these issues are listed below.

TR-E-I-23: This isolate was identified as a “Historic wood frame hitch”. This isolate is actually an axel off of a horse drawn wagon (most likely the rear axel).

TR-E-15: This site is listed as one oval rock cairn 1.5m X 2m in size. The size and shape of this cairn is similar to the other burial cairns discovered in this area, and the

function of this cairn should be examined closely by Tribal Representatives for their input.

TR-F-21: No (CRIS) site form was included for this site. Only the photo which was blurred, and the 7.5' Quad site location map where provided to the landowner.

TR-E-23: This site is listed as “three one-tier stone circles” and go on to say that “Abundant cobbles of the same material present in the area, and it is uncertain as whether the resource is cultural or not”. If ICF had doubts about this site being real they should not have recorded it as a site. Look at the situation on TR-E-44 as an example of a stone circle site ICF claimed was a site.

TR-E-43: This site is listed as a “one-tier rock cairn approximately 20cm in diameter”. The photo shows a feature that resembles a rock lined hearth that is commonly found as a hearth associated with stone circle sites in the area.

TR-E-52: This site was documented as a “one-tier rock alignment of 4 local cobbles and one small petroglyph”. The photos show all of the rocks loose on the surface with no indication that the stones were ever imbedded in the sod as should be expected if the rocks were old enough to be associated with a prehistoric site. The photo of the petroglyph is of poor quality, and better photos and a detailed drawing should have been included with the site form.

TR-E-53: This site was documented as “two rock cairns measuring 2.5m X 2.5m and 1.5m X 2m in diameter. In the documents provided to the landowners, cairns are described as piles of rocks of various sizes, typically ranging from several stones to large stacks of rocks. The photos with the site form show stone circles as described in the site forms, and stacked (to model the natural slope). These features are typical of rock hunting blinds found in the Tongue River area, on the hill tops east of TR-F-BO45 (Rocker Six Corral), and throughout the western edge of the plains of Colorado, Montana and Wyoming.

TR-E-54: This site was documented as “three rock cairns measuring 2m X 3m, 2m X 2m, and 2m X 2m in diameter. As described above in regards to the actual description the features, they are not cairns, but stone alignment features that form possible hunting blinds. These features are typical of rock hunting blinds found in the Tongue River area, on the hill tops east of TR-F-BO45 (Rocker Six Corral), and throughout the western edge of the plains of Colorado, Montana and Wyoming.

TR-E-58: This site was documented as “two rock cairns measuring 2.5m X 3m, and 2m X 1.5m in diameter. Once again, these features are described by ICF as linear features, but are called cairns (stacks of rocks).

TR-E-60: This site was documented as one tipi ring constructed of 8 sandstone cobbles and measures approximately 4m in diameter, and one semi-circular rock alignment 1m in diameter. I would question the reality of this tipi ring having only 8 rocks to determine a

stone circle 4m in diameter. Also, the rocks visible in the photo appear to be too small to be part of a tipi ring as previously mentioned in relation to site TR-E-44 documented by ICF.

Summary: During the survey conducted during the course of this project, we examined 20 sites documented by ICF in 2014 on private land. While examining these sites and one area where ICF said they found nothing, 36 undocumented sites were discovered including 5 cairns, 7 lithic scatters, 2 lithic procurement sites, 1 rock shelter, 2 historic rock art sites, 2 stone circle sites, 6 probable prehistoric burials, 2 historic burials, 1 TCP, 6 historic sites, and 4 isolates. Ground visibility in the project area was mostly poor (0% to 20%) as a result of heavy vegetation cover, and I'm sure that we would have discovered more sites and more cultural material on the sites we did document if ground visibility had been better.

Overall, the quality of the survey documentation and maps was problematic with inaccurate and incomplete documentation provided on most the site forms, several of the 7.5' Quad maps provided with site forms, and even the project maps had sites plotted in the wrong place or omitted from the maps. We found more lithic material on the majority of the sites ICF documented as lithic scatters, and in one case a site listed as a lithic isolate with 4 artifacts turned out to be a large concentration of lithic material with an obvious buried component. There were also several sites that were miss-identified, and it was questionable if some of the sites were even cultural, or old enough to be considered historic properties.

Field notes and photos (with the exception of the TCP and burial sites) will be provided as a separate document. Information on the TCP and burial sites will be provided **as needed** after tribal representatives have had the opportunity to comment on the data collected during the documentation process.

For further information contact me at chris_finley@nps.gov.

Chris C. Finley

Exhibit 20

Population Status and Trends of Big Game and Greater Sage-Grouse in Southeast Montana and Northeast Wyoming



Photograph by John Ellenberger

Mule Deer Buck

July 2015

Population Status and Trends of Big Game and Greater Sage- Grouse in Southeast Montana and Northeast Wyoming

**Prepared for the
National Wildlife Federation
And
Natural Resources Defense Council**

By:

John H. Ellenberger
johncone@q.com

&

A. Eugene Byrne
WMCA_Gene@MSN.com

of

**Wildlife Management Consultants
And Associates, LLC
566 36 Road
Palisade, Colorado 81526
(970) 270-6082
www.wlmgt.com**

EXECUTIVE SUMMARY

The National Wildlife Federation retained Wildlife Management Consultants and Associates, LLC to gather and analyze data for deer, elk, pronghorn and greater sage-grouse populations that occupy portions of southeastern Montana and northeastern Wyoming. Specifically, the study area includes the portion of Montana bounded on the north by Interstate 94, O'Fallon Creek and US Highway 12; on the east by the North Dakota and South Dakota state lines; on the south by the Wyoming state line and on the west by Interstate 90 and State Highway 47, with the exception of lands included in Northern Cheyenne and Crow Indian Reservations. The study area also includes the portion of Wyoming bounded on the north by the Montana state line; on the east by the South Dakota state line; on the south by US Highway 20 and the North Platte River and on the west by Interstate Highways 25 and 90.

Furthermore, we were requested to prepare a report of our analysis of these data that would "interpret trends in populations and harvest and provide insight into challenges to the populations' viability." One goal of the report was to determine which populations may be sensitive or vulnerable to habitat loss or degradation caused by development. For the purpose of this report, development includes, but is not limited to, coal mining, drilling for oil and gas, wind power, electrical transmission lines and natural gas pipe lines, urbanization and cultural development and habitat conversion (e.g., chemical or mechanical treatment of sagebrush habitat to increase grasses and herbaceous vegetation). This report is intended to provide information for sportsmen and the general public about the status of mule deer, elk, pronghorn and greater sage-grouse populations in the above mentioned areas, especially as it relates to hunting recreation and watchable wildlife opportunities.

Inventory and harvest data for mule deer, elk, pronghorn antelope, and greater sage-grouse from Montana Fish, Wildlife and Parks and Wyoming Game and Fish Department were used for the analysis. The time frame for the analysis began in 1980 and continued through 2012 and 2013 in some instances. Once the raw data was obtained from the 2 wildlife agencies, it was entered into excel spread sheets to facilitate comparisons and analyses. Big game data used in the analyses included the following; male harvest and total harvest for all seasons and methods of take, total hunters, hunter success rates, herd composition data (males/100 female ratios and young/100 female ratios) and annual estimates of population size for each herd unit or hunting district. The data were used to calculate the following products for each category listed above (total harvest is used here as an example); maximum harvest, minimum harvest, average harvest for all years and average harvest by decade. In addition, excel was used to calculate long-term trends for the data via linear regression. Charts were created using excel to provide a graphic display of the data for population size, male/100 female ratios, young/100 female ratios, male harvest, total harvest, total hunters, and hunter success rates.

Throughout this report we have described the vulnerability of deer, pronghorn and greater sage-grouse populations and to a lesser extent elk to stochastic events such as severe winters and drought. As human development causes additional impacts to wildlife habitat these populations are forced to exist on less habitat or lower quality habitat than has existed in the past in addition to coping with the natural variation that occurs in the habitats and environments they occupy.

Analysis of data for 27 big game herd units or hunting districts was completed for this project, 8 mule deer, 7 elk and 12 pronghorn. In addition, a review of information and data was completed for 2 greater sage-grouse management areas.

For big game we used information from the literature and our professional experience and opinions to evaluate the status of the big game herds.

Information that we evaluated for each herd unit (Wyoming) and hunting district (Montana) included the following:

- 2012 values for young/100 female ratios and a comparison to the long-term average for young /100 female ratios.
- Long-term trend for young/100 female ratios.
- 2012 values for male harvest and a comparison to the long-term average for male harvest.
- Long-term trend for male harvest.
- 2012 values for total hunters and a comparison to the long-term average for total hunters.
- Long term trend for total hunters.
- To a lesser extent, estimates for population size were also assessed and were compared to established population objectives for each herd, when available.

Of the big game species addressed in this analysis, mule deer and pronghorn appear to be the most vulnerable. Deer and pronghorn populations analyzed in this report have either shown declines in population size or productivity or both in the past 32 years. Such declines have direct impacts on hunters and hunting opportunity in the form of lower hunter success rates, decreased harvest, possible decreases in trophy quality of animals harvested and more conservative hunting seasons. We have significant concerns that losses of habitat due to development will result in further reductions in populations and productivity of the deer and pronghorn herds in question, resulting in increasingly conservative hunting seasons and lower numbers of available licenses.

We believe that elk are not as vulnerable as mule deer and pronghorn to habitat loss or degradation due to development. This is probably due to their broader food habits and adaptability (Hanley and Hanley 1982 and Thompson and Henderson 1998). However, a likely result of development on public lands will be displacement of elk from seasonal ranges or shifts in periods of use of these seasonal ranges. Displacement of animals will likely result in increased use of private lands by elk resulting in increasing levels of conflict. Increased conflicts often results in increases in game damage or more demands for reductions in elk populations by private land owners which will, in the long run, mean less hunting opportunity.

Mule Deer

Eight mule deer herds were examined in this analysis, 3 in Montana and 5 in Wyoming. Of the 8 herds evaluated only 1 was judged to be in good condition, Wyoming herd unit 751 (Black Hills). Five herds were judged to be in fair condition; Montana hunting districts 702 (Yellowstone Pine Hills), 704 (Powder Pine Hills) and 705 (Prairie/Pines-Juniper Breaks) and Wyoming herd units 319 (Powder River) and 755 (North Converse). Wyoming herd units 320 (Pumpkin Buttes) and 740 (Cheyenne River) were considered to be in poor condition. Three herds had additional problems or issues. Wyoming deer herd units 319 (Powder River), 320 (Pumpkin Buttes) and 740 (Cheyenne River) had short-term trends of 3-5 years of recent declines in population size along with long-term declines for recruitment (young/100 females). These populations are especially vulnerable to additional habitat loss or degradation. If habitat loss or degradation occurs with these 3 herd units, increases in population size are unlikely or very slow to occur.

Table 1. Summary of mule deer population data and trends

Unit	Pop. Obj.	2012 Pop. Size	Avg. Pop. Size	Pop. Trend	2012 Yng./100 Fem.	Avg. Yng./100 Fem.	Yng./100 Fem. Trend	2012 Male Harvest	Avg. Male Harvest	Male Harvest Trend	2012 Total Hunters	Ave. Total Hunters	Total Hunter Trend	Herd Rating
M-MD-702	NA	105	153	D	84	68	I	877	1,083	D	2,416*	2,656	D	F
M-MD-704	NA	538	524	S	63	69	D	1,574	2,238	D	4,695*	4,841	I	F
M-MD-705	NA	492	447	I	56	66	D	1,553	1,937	D	4,141*	5,008	D	F
W-MD-319	52,000	36,300	45,490	I	75	68	D	2,036	3,191	D	3,602	5,826	D	F
W-MD-320	13,000	9,600	11,117	S	64	69	D	633	729	D	1,046	1,467	D	P
W-MD-740	38,000	17,367	29,150	I	44	74	D	1,255	2,339	D	2,511	4,719	D	P
W-MD-751	20,000	19,505	20,040	I	76	74	I	1,253	1,917	D	3,569	5,845	D	G
W-MD-755	9,100	6,004	8,294	I	75	75	D	332	568	D	550	1,057	D	F
Unit explanation - M-MD-702 = Montana mule deer hunting district 702														
W-MD-319 = Wyoming mule deer, herd unit 319														
Trend: I - increasing, S - stable, D - decreasing														
Herd Rating: G - good, F - fair, P - poor														
NA - not applicable														
ND - no data														
* 2011 data														
Population estimates are for a Montana trend count area that is smaller in size than														
a hunting district														

Seven elk herds were evaluated in this analysis, 3 in Montana and 4 in Wyoming. Five of the 7 herds didn't receive a rating due to incomplete data. Readers that are interested in these hunting districts or herd units should refer to the detailed evaluations for each of them in the body of the report and tables for each herd unit in the appendix. Both Wyoming elk herd unit 320 (Fortification) and elk herd unit 344 (New Rochelle) were rated in the good category. The situation for elk seems to be almost exactly opposite of what is occurring for mule deer. However, there is significant concern that additional habitat loss or degradation due to development, prolonged drought or severe winters may displace elk populations, causing increased game damage problems on private lands. Such issues will likely result in demands for further reduction in long term population objectives for elk. If long-term population objectives for elk are reduced, it will eventually result in further decreases in harvest and hunter opportunity.

Table 2. Summary of 2012 elk population data and trends

Unit	Pop. Obj.	2012 Pop. Size	Avg. Pop. Size	Pop. Trend	2012 Yng./100 Fem.	Avg. Yng./100 Fem.	Yng./100 Fem. Trend	2012 Male Harvest	Avg. Male Harvest	Male Harvest Trend	2012 Total Hunters	Avg. Total Hunters	Total Hunters Trend	Herd Rating
M-E-702	NA	ND	NA	ND	71	NA	NA	23	14	I	523	277	I	NA
M-E-704	NA	1,070	NA	ND	44	43	D	54	33	I	719	656	I	NA
M-E-705	NA	ND	NA	NA	53	NA	NA	26	17	I	277	212	I	NA
W-E-320	150	500	244	I	77	48	I	13	16	I	80	71	I	G
W-E-344	NA	741*	368	I	60	45	I	22	16	I	164	73	I	G
W-E-740	500	ND	NA	I	ND	NA	NA	171	97	I	1,416	586	I	NA
W-E-743	NA	ND	NA	NA	NA	NA	NA	20	14	I	71	52	I	NA
Unit explanation - M-E-702 = Montana elk hunting district 702														
W-E-320 = Wyoming elk herd unit 320														
Trend: I - increasing, S - stable, D - decreasing														
Herd Rating: G - good, F - fair, P - poor														
NA - not applicable														
ND - no data														
* 2011 data														

Pronghorn

Of the twelve pronghorn herds evaluated in the analysis, only 1 of the herds didn't receive a rating due to incomplete data, Montana hunting district 702 (Yellowstone Pine Hills). Three pronghorn herds received a good rating; Wyoming herd units 309 (Pumpkin Buttes), 318 (Crazy Woman) and 353 (Ucross). Seven unit received a fair rating; Montana hunting district 705 (Prairie Pines-Juniper Breaks). Wyoming herd units 308 (Clearmont), 316 (Highlight), 339 (North Black Hills), 351 (Gillette), 740 (Cheyenne River) and 748 (North Converse). One unit received a poor rating, Montana hunting district 704 (Powder Pine Hills). In addition, Wyoming pronghorn herd units 740 (Cheyenne River) and 748 (North Converse) have short-term trends of 2-3 years of recent declines in population size along with long-term declines for productivity (young/100 female ratios) that make these herds especially vulnerable to loss of habitat. If habitat loss or degradation occurs within these 2 herd units, increases in population size are going to be very slow or unlikely.

Table 3. Summary of 2012 pronghorn population data and trends

Unit	Pop. Obj.	2012 Pop. Size	Avg. Pop. Size	Pop. Trend	2012 Yng./100 Fem.	Avg. Yng./100 Fem.	Yng./100 Fem. Trend	2012 Male Harvest	Avg. Male Harvest	Male Harvest Trend	2012 Total Hunters	Avg. Total Hunters	Total Hunters Trend	Herd Rating
M-PH-702	NA	2,097	2,932	D	ND	NA	I	98	244	I	198	518	S	NA
M-PH-704	NA	1,079	936	I	35	29	D	190	623	D	328	1,234	D	P
M-PH-705	NA	604*	1,211	I	86	93	D	315	1,081	D	550	2,119	D	F
W-PH-308	3,000	4,300	4,500	I	65	66	D	244	354	D	512	588	D	F
W-PH-309	18,000	35,500	22,670	I	71	83	D	1,479	1,361	D	2,699	2,105	S	G
W-PH-316	11,000	10,000	11,527	S	47	77	D	528	532	D	1,076	963	D	F
W-PH-318	7,000	12,100	8,842	I	82	84	D	1,086	719	D	1,968	1,094	D	G
W-PH-339	14,000	12,500	13,746	I	82	83	D	415	971	D	657	1,516	D	F
W-PH-351	11,000	10,300	12,509	I	70	65	D	794	709	I	979	1,028	I	F
W-PH-353	2,500	7,400	4,833	I	84	74	D	459	308	I	802	488	S	G
W-PH-740	38,000	31,065	31,140	I	63	78	D	2,512	2,667	S	4,826	4,492	D	F
W-PH-748	28,000	20,432	27,150	I	66	83	D	1,759	1,944	D	3,822	3,072	D	F
Unit explanation - M-PH-702 = Montana pronghorn hunting district 702														
W-PH-308 = Wyoming pronghorn herd unit 308														
Trend: I - increasing, S - stable, D - decreasing														
Herd Ratings: G - good, F - fair, P - poor														
NA - not applicable														
ND - no data														
Population estimates are for a Montana trend count area that is smaller in size than a hunting district														

Sage-grouse

Population Trends

Northern sage-grouse populations have experienced periodic fluctuations in southeastern Montana and northeastern Wyoming over the years. Trends for the average number of males per lek and the trend of the percentage of occupied leks versus unoccupied leks seem to be the best indicators of sage grouse abundance.

Lek data for the core area of southeastern Montana indicates that the sage-grouse populations in the area have not exhibited a long term decline and the peak population actually occurred in the mid-2000s. This was followed by a decline that was probably a result of a West Nile virus (Foster et al ND). However, pre-1980 historic lek data is not available for the core area. As a result, a claim that 2002 was the peak for northern sage-grouse populations in the core area needs to be considered cautiously.

Trends for sage-grouse populations in northeastern Wyoming appear to be substantially different. Since 2006, sage-grouse numbers have declined significantly. The current decreasing trend

could be a combination of the cyclic nature of sage-grouse populations combined with documented influences from fire, land conversion, West Nile virus and energy development in the Powder River Basin. The last peak occurred in 2006 and 2007 (> 30 males per lek) which actually exceeded the previous peak which occurred in 2000. The highest level was over 50 males per lek in 1979.

Hunting and Harvest

Sage-grouse hunting seasons in both states have become more conservative with shorter seasons and smaller bag and possession limits as populations have fluctuated. Hunting regulations in Montana have changed a few times since 1990. In 1994 the bag limit on sage grouse changed from 4 to 3 per day and the possession limit changed from 16 to 12. In 1996, the bag limit changed again to 2 sage grouse per day with a possession limit of 6. The bag limit increased to 3 sage grouse per day in 2000, but the possession limit stayed at 6. In 2005, the bag limit changed from 3 to 2 sage grouse per day and the possession limit decreased from 6 to 4. The hunting season length on sage grouse also decreased during this time. From 1990-95 the season dates were Sep.1-Dec.15, and then in 1996 the season was shortened to Sep. 1-Nov.1, which is the current hunting season structure. Harvest information indicates a declining sage grouse harvest from approximately 1,000 in 2003 to 386 in 2009. Sage grouse hunter days were sporadic ranging from approximately 850 to 1,400 hunter days annually from 2007-09. Current hunter days are similar to sage grouse hunter days from 2004-06 which ranged from approximately 900 to 1,300 hunter days annually (Beyer et al 2010).

Sage-grouse hunting seasons within the Northeast Wyoming Sage-Grouse Working Group Area are managed concurrently with other open areas in the state. Prior to 1995, the statewide hunting season opened September 1 and closed September 30. Concerns with decreasing sage-grouse populations and the impact of hunting adult hens in early September initiated changes to more conservative hunting seasons. Beginning in 1995, the opening date was moved to the third Saturday in September with hunting seasons lasting 14 – 17 days. Bag and possession limits were 3 birds per day and 6 birds in possession. More conservative hunting seasons were enacted in 2002 when the opening day was moved to the fourth Saturday in September and the closing date to the first Sunday in October resulting in a 9 day season. The bag and possession limits were reduced to 2 and 4 birds, respectively. A Wyoming Game and Fish Commission Emergency Order was approved in 2003 to close the hunting season in Sheridan, Johnson and Campbell Counties due to documented loss of sage-grouse to West Nile virus. This area included portions of Management Areas 35 – 38 and 40 – 41. The hunting season was resumed in this area for 2004 because increased monitoring of radio collared birds indicated that West Nile virus, while still present, had not caused a statistically significant population decline.

Over the last ten years, sage-grouse harvest for the Northeast Wyoming Sage-grouse Working Group area has ranged from a high of 2,515 birds in 2000 to a low of 104 birds in 2003 when Sheridan, Johnson and Campbell Counties were closed to hunting. Only 120 birds were harvested in 2002 when more conservative season dates and bag/possession limits were enacted. Hunter numbers have generally reflected harvest, with more hunters going afield when populations are high. Such was the case in 1999 and 2000 when more than 2,500 birds were harvested annually.

Conservation Strategies

Wyoming and Montana have both implemented core area strategies in an attempt to better protect sage-grouse and their habitat. For Wyoming, Governor Freudenthal issued Executive Order 2008-2 in August 2008 outlining the core area strategy with 21 recommendations that conserve Wyoming's most important sage-grouse habitats while allowing for natural resource development outside core areas. Statewide, core areas accounted for approximately 34% of the current sage-grouse range while including leks where 81% of males were counted during peak periods of attendance in 2008. However, within a three county area of the Powder River Basin (Campbell, Johnson and Sheridan Counties), core areas were designated based on CBNG

development patterns along with lek density data thereby encompassing leks where only 28% of males were counted during peak periods of attendance in 2008.

Subsequent to the 2010 Wyoming gubernatorial election, Governor Mead signed a 2011 version of the Executive Order that reiterated and clarified the Wyoming Core Area Strategy. In addition, on April 5, 2013, Governor Mead issued Executive Order 2013-3, *Greater Sage-grouse Core Area – Grazing Adjustments*, which addressed livestock grazing and sage-grouse as well as coordination between the state and federal agencies in managing Wyoming's federal rangelands.

Montana has followed Wyoming's lead in developing a sage grouse conservation program based upon the core area principles. The program was initiated on Sept. 9, 2014 when Gov. Steve Bullock signed Montana Executive Order Number 10-2014. Montana has the second largest GSG population among the western states. Their plan closely mirrors the Wyoming executive order and plan.

While the "Core Area Strategy" concept is a step in the right direction and should provide additional protection for sage-grouse habitat in the future for both states, a report issued by the Conservation Objectives Team (**COT**), a part of the Sage Grouse Task Force, paints a bleak picture for the future of sage-grouse in northeastern Wyoming and to lesser extent, southeastern Montana. In summary, the report prepared by the **COT** (U.S. Fish and Wildlife Service 2013) listed energy development, infrastructure, improper livestock and/or wildlife grazing practices, weeds and annual grasses, mining and recreation as broad scale threats to sage-grouse in the Powder River Basin portions (NEWLWG area plus a small section of Montana) of the Great Plains Management Zone with localized threats being sagebrush elimination, fire, conifer encroachment, and urbanization. The report estimated a 16.5% probability of the subpopulation of breeding birds being below 500 by 2037 and an 86.2% probability of the subpopulation of breeding birds declining below 500 by 2107.

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INTRODUCTION

The National Wildlife Federation retained Wildlife Management Consultants and Associates, LLC to gather and analyze data for deer, elk, pronghorn and greater sage-grouse populations that occupy portions of southeastern Montana and northeastern Wyoming. Specifically, the study area includes the portion of Montana bounded on the north by Interstate 94, O'Fallon Creek and US Highway 12; on the east by the North Dakota and South Dakota state lines; on the south by the Wyoming state line and on the west by Interstate 90 and State Highway 47, with the exception of lands included in Northern Cheyenne and Crow Indian Reservations. The study area also includes the portion of Wyoming bounded on the north by the Montana state line; on the east by the South Dakota state line; on the south by US Highway 20 and the North Platte River and on the west by Interstate Highways 25 and 90.



Fig. 1. Study area – Montana portion



Fig. 2. Study area – Wyoming portion

Furthermore, we were requested to prepare a report of our analysis of these data that would “interpret trends in populations, harvest and provide insight into challenges to the populations’ viability.” One goal of the report was to determine which populations may be sensitive or vulnerable to habitat loss or degradation caused by development. For the purpose of this report, development includes, but is not limited to, coal mining, drilling for oil and gas, wind power, electrical transmission lines and natural gas pipe lines, urbanization and cultural developments and habitat conversion (e.g., chemical or mechanical treatment of sagebrush habitat to increase grasses and herbaceous vegetation). This report is intended to provide information for sportsmen and the general public about the status of wildlife populations in the above mentioned areas, especially as it relates to hunting recreation and watchable wildlife opportunities.

The intended audiences are lay people and citizen scientists that have an interest in understanding basic wildlife management principles and reviewing management data sets for the project area. Commonly known facts and figures about big game biology are not discussed. Specific and technical facts discussed in this document are cited with their literature reference. Reference materials used to produce this report are listed in the Literature Cited and References section of the report. If more information is needed on some of these subjects, the authors direct the inquiries to these sources. Many of these documents can be accessed on the internet.

The study area provides habitat for a number of mule deer, elk and pronghorn herds as well as habitat for greater sage-grouse. Each state uses slightly different terminology to describe areas occupied by the wildlife. Herd units (WG&F) are large geographic areas that define the year around habitat of a specific big game herd. Hunt areas (WG&F) and hunting districts (MFWP) are generally smaller areas within herd units that are used to define a geographic area, distribute hunter pressure and allocate hunting licenses. For Montana, the study area provides habitat for 3

mule deer herds, 3 elk herds, 3 pronghorn herds and a greater sage-grouse management area. For Wyoming, the study area provides habitat for 5 deer herds, 4 elk herds, 9 pronghorn herds and a greater sage-grouse management area.

Inventory and harvest data for mule deer, elk, pronghorn antelope, and greater sage-grouse from Montana Fish, Wildlife and Parks and Wyoming Game and Fish Department were used for the analysis. The time frame for the analysis began in 1980 and continued through 2012 and 2013 in some instances. Once the raw data was obtained from the 2 wildlife agencies, it was entered into excel spread sheets (Microsoft Corporation) to facilitate comparisons and analysis. Data used in the analysis included the following; male harvest, total harvest for all seasons and methods of take, total hunters, hunter success rates, herd composition data (males/100 female ratios and young/100 female ratios) and annual estimates of population size for each herd unit or hunting district. The data were used to calculate the following products for each category listed above (total harvest is used here as an example); maximum harvest, minimum harvest, average harvest for all years and average harvest by decade. In addition, excel was used to calculate long-term trends for the data using linear regression. Charts were created using excel to provide a graphic display of the data for population size, male/100 female ratios, young/100 female ratios, male harvest, total harvest, total hunters, and hunter success rates. Spread sheets for all herd units in the analysis are included in the appendix.

SECTION I

BIG GAME BIOLOGY, ECOLOGY AND MANAGEMENT

Throughout the years, species experts, panels and working groups have assembled information concerning threats to wildlife species. Listed below is information on a species by species basis about what activities, practices, developments and phenomena are considered as threats or problems for the following wildlife; deer, elk and pronghorn antelope.

Mule Deer

Due to the perceived decline of mule deer in many western states during the latter part of the 20th century, wildlife agencies have attempted to determine specific causes for the decline (Workman and Low 1976, Gill 2001). In addition, directors of the agencies from the Western Association of Fish and Wildlife Agencies created a Mule Deer Working Group in 1998 to address issues and questions generated by sportsmen and other members of the public. The Mule Deer Working Group produced a number of products and reports, one of which was Mule Deer Conservation: Issues and Management Strategies (de Vos et al. 2003). In the report, environmental impacts and habitat changes that have negatively affected mule deer were enumerated. Following are the impacts and changes presented in the order they were listed in the publication. Recommendations for tactics and strategies that could be used to mitigate management problems associated with the impacts and changes were also provided.

- Fire suppression and livestock grazing
- Oil-gas-mineral exploration and extraction
- Urban development
- Migration barriers
- Cheatgrass invasion
- Mule deer over-population

Elk

In contrast with the decline that has occurred in mule deer populations across the west, elk populations have grown substantially in most states since the early part of the 20th century. Despite the ability of elk populations to grow and prosper in conjunction with human population

growth and development, there are aspects of their life cycle and biology that require protection in order for them to continue to prosper.

- Protection of calving grounds and nursery areas
- Provide large areas of secure habitat
- Protect and preserve migration pathways and corridors
- Prevent elk over-population

Pronghorn

Pronghorn have rebounded from historic low populations in the early part of the 20th century that occurred in most western states. In spite of these apparent successes there are challenges to maintaining pronghorn populations at their current level. Wildlife professionals involved in pronghorn management have participated in workshops to discuss management issues. The Biennial Pronghorn Workshop has been held every 2 years since 1965. The goal of the workshop is “to exchange information and encourage the perpetuation of sustainable wild herds of pronghorns as an ecological, aesthetic and recreational natural resource on public and private western rangelands at their most productive levels consistent with other land uses” (Lee et al. 1998). In addition the workshop periodically publishes Pronghorn Management Guides which provide recommendations for suggested practices and techniques for managing pronghorn and their habitat (Lee et al. 1998). As stated by Lee et al. (1998), “the objective of these guides was to provide pronghorn managers with the best information available for managing and perpetuating pronghorn and their habitats.” A feature of the guides is a list of specific problems or issues with pronghorn management.

- Livestock production issues
- Fences
- Industrial development
- Crop depredation

Each general category is further divided into more specific issues that need to be addressed. Of particular interest under the general category of industrial development are the impacts of oil and gas exploration, development and production to pronghorn, specifically habitat loss and animal displacement

Big Game Biology and Ecology

Of the big game species covered in this report, mule deer and pronghorn are much more susceptible than elk to the negative influences of severe weather, habitat degradation, competition with other ungulates, human population growth, energy development and predation (Gill 2001). Obtaining adequate nutrition at different times of the year is important for all big game but seems more problematic for deer and pronghorn. Deer, especially fawns, must arrive on winter range in good condition with adequate body fat reserves in order to survive even winters of moderate severity. Fawns are much more susceptible than adults to starvation due to the fact that so much of the energy they derive from the forage they consume is used for development and growth instead of being stored as body fat. Also, once mule deer arrive on winter ranges they need adequate supplies of high quality, easily digestible forage in order to survive, much less maintain condition and body weight (Mautz 1978).

High quality, easily digestible winter forage for mule deer consists of current annual growth (plant growth from last summer) (leaves, buds and stems) of shrubs such as big sagebrush (*Artemisia spp.*), mountain mahogany (*Cercocarpus spp.*), serviceberry (*Amelanchier spp.*), bitterbrush (*Purshia spp.*) and saltbush (*Atriplex spp.*). Forage items such as senescent grasses and forbs are not good winter forage for mule deer due to the high percentage of cellulose in the cell walls of these plants. Deer can't extract enough energy from senescent grasses and forbs due to the long period of time needed to break down cellulose in their rumens. Mule deer and pronghorn have relatively small rumens when compared to elk and need to be able to rapidly pass forage through their digestive tracts in order to extract enough energy to maintain body temperature and minimize loss of body weight (Hanley 1982 and Hanley and Hanley 1982).

In comparison, elk due to their larger rumens, can utilize senescent grasses and forbs found on winter ranges. Also, elk are better adapted to digging in deep snow to utilize this forage. Their larger rumen allows them more time to digest cellulose and extract energy from food items that deer can't easily digest (Hanley and Hanley 1982).

How does this all relate to vulnerability of big game to habitat degradation or loss due to development or other disturbances? It is much easier to reclaim disturbed or damaged big game ranges to grasses and forbs than to shrubs. Also, if shrubs can be established, it takes many more years for shrubs to develop to the point where they can provide forage for big game than required for grasses and forbs. As a result, reclamation of damaged and disturbed big game ranges will likely benefit elk more than mule deer and pronghorn.

Factors Influencing Big Game Populations

It would be less difficult to manage big game populations if there were a detectable response in a big game herd every time there was a slight change in weather patterns, a new road was built into previously inaccessible habitat or wildfire burned a large portion of winter range. In reality, it is very difficult to establish cause and affect relationships between perturbations in habitat and responses in wildlife populations. One of many challenges in wildlife management is the difficulty in deciphering which factor or factors is the likely culprit responsible for a change in wildlife density, survival or productivity.

The following discussion is an effort to list some of the many factors that can affect wildlife populations and the data that is collected in an attempt to evaluate them. These factors can be grouped into 2 major categories, natural and anthropogenic. Usually, with the exception of catastrophic wild fire and severe winter weather, the impact of natural factors on wildlife populations is general, chronic and subtle. Conversely, anthropogenic impacts are more likely to be specific, acute and obvious.

Natural Factors

Severe winter weather lowers survival rates (primarily of young of the year), decreases fitness of surviving animals, may lower survival rates of young born following the severe winter and may decrease fecundity in females for the following year. In addition, animals concentrated on winter ranges by severe winter conditions can over-utilize forage plants resulting in an overall decrease in range productivity. Wildlife agencies generally respond to such events by establishing more conservative hunting seasons with fewer licenses available for hunters.

Drought can also decrease survival due to poor forage production, which can have a negative impact on lactating females which can lead to starvation of young or increased susceptibility to predation (Pojar and Bowden 2004). Productivity may also decrease due to poor body condition of adult females. If drought is severe or prolonged it may have significant effects on adult survival rates (Bender and Browning 2003). Effects of drought are expressed in data as decreases in density and decreases in young and yearling recruitment. Prolonged drought may also require reassessment of long-term population objectives for individual herd units. In such cases, population objectives may be decreased substantially due to loss of habitat. This may result in a temporary increase in limited antlerless licenses to reduce population size. However, the long-term reduction in population will generally mean overall reduced opportunity for hunters. Wildlife agencies respond to drought in a fashion similar to severe winters by establishing conservative hunting seasons that decreases opportunity for hunters.

Loss or changes in habitat due to plant diseases, plant succession or noxious weed invasion can have a negative impact on big game populations. These events may occur over long periods of time and the magnitude of the impacts are often difficult to detect by the casual observer. Effects on wildlife populations are slow to occur but usually are expressed as gradual decreases in density, declines in young/100 female ratios or decreases in survival rates. Wildlife agencies usually respond to such events by recommending conservative seasons that limit hunter opportunity.

Anthropogenic Factors

Hunting season structure arguably has the potential to impact big game populations and harvest as much or more than any other anthropogenic factor. For big game, season structure includes items such as season dates, season length, methods of take as well as other features such as antler-less animal harvest and totally limited licenses. On the animal side of the equation, season structure can have significant impacts on animal density and age and sex composition. On the hunter side of the equation hunting season structure can directly affect hunter numbers and harvest.

Socio/economic factors can also have significant impacts on wildlife populations and hunter opportunity. An example of one of these factors is land ownership. In units with a large amount of public land, total harvest can be relatively high but hunter success low due to high hunting pressure. In units where most of the area is private land the opposite situation is more likely to occur, with relatively low harvest accompanied by high hunter success rates due to low hunting pressure and a relatively large number of animals.

Development can come in many types and forms and as such has significant potential to impact animal populations and hunting opportunity. Residential development, depending on density of housing units and location, can displace animals and impede migrations and/or seasonal movements of wildlife. Recreational development such as ski areas can have significant impacts by displacing animals and interrupting animal movements. Industrial development such as those for mining and energy development can degrade large tracts of habitat and displace animals. In the above mentioned scenarios, animal density is usually reduced and hunter opportunity decreases as a result. With intensive development of any of the above examples, hunting is usually precluded, especially with center fire firearms. However, over time, some of these impacts may have the potential for mitigation by habitat restoration.

Potential Impacts of Development

Projections for development of many areas in southeastern Montana and northeastern Wyoming are a significant concern for wildlife managers. Intensive development for oil and natural gas, coal and wind power has the potential to create huge impacts to wildlife habitats in many areas of the two states.

Typical development of an area for natural gas exploration, development and production consists of construction of drill pads, roads, pipelines, compressor stations and wastewater ponds. In a development scenario habitat loss is both direct and indirect. Direct loss of habitat includes loss of space and forage due to actual construction of the oil field infrastructure. Indirect loss of habitat is due to animal avoidance of a larger area around the zones of drilling activity and infrastructure in an attempt to keep away from human disturbance.

Direct loss of habitat due to drill pad construction, roads, pipelines, etc. is a relatively small percentage of the total habitat at low drill pad density. At 16 drill pads per square mile (one drill pad/40 acres), approximately 32 acres of habitat is lost to drill pad construction. An estimated additional 14.5 to 24 acres of habitat is lost to road construction depending on road width and length resulting in a direct loss of 46 to 56 acres or 7 to 9% of available habitat. This estimate doesn't include any loss of habitat due to other construction activities such as pipelines, compressor stations and wastewater ponds. In a worst-case scenario of 64 drill pads per square mile (one drill pad/10 acres), approximately 128 acres is lost to drill pad construction. In addition, an estimated 28 to 47 acres is lost to road construction resulting in a direct loss of habitat of 156 to 175 acres or roughly 27% of the habitat (Ellenberger and Byrne 2007).

Indirect loss of habitat due to animal avoidance of human activity or structures is more difficult to measure. Recent information from studies conducted near Pinedale, Wyoming involving mule deer and energy development (exploration, development and production of natural gas) has shown greater than previously reported impacts on habitat use by mule deer (Sawyer et al.

2006). In this study, 41% of the areas previously reported as high use areas by deer had changed to medium-low or low use. In addition, areas with the highest deer use were > 2.7 km away from drill pads (Sawyer et al. 2006). Impacts of energy development on survival, fecundity and productivity of mule deer in this area are yet to be studied.

Impacts of wind energy development on big game wildlife and sage grouse are relatively unknown. Few studies have been conducted on the impacts of wind energy development on big game, especially for the magnitude of wind energy development that is proposed in some areas in Wyoming. However, wind energy development does include road building, construction activities and increased human activity and will likely have significant temporary impacts that are similar to those that occur as the result of the development of oil and gas fields. Displacement of big game from habitat is a likely scenario as the result of wind energy development (Kuvlesky et al. 2007). The magnitude of this displacement is yet to be determined.

Like development for oil and gas, wind energy development will occur in phases. Displacement of wildlife will likely be most significant during the construction phase. However, there is little or no information available on the impact of large scale wind energy development once the construction phase is completed and energy production begins. The amount of human activity needed to maintain windmills and energy transmission lines is an unknown entity. If human activity is kept to a minimum, how well animals will habituate to the constant movement and noise created by the turbines is also unknown.

Impacts of surface mining for coal on big game and greater sage-grouse are significant and localized. By definition, habitat is destroyed in a surface mining operation by the removal of overburden to access the underlying coal seam(s). Also, additional habitat is disturbed or destroyed by the construction of infrastructure; haul roads, conveyor belt systems, administrative and maintenance buildings and stockpiling of top soil. Additional habitat may be lost if a power plant is erected nearby to take advantage of the mined coal. The concepts of direct and indirect loss of habitat also come into play in surface mining of coal. The portion of the area being actively mined and associated infrastructure represent the direct loss of habitat. Indirect loss of habitat is related to the amount of activity and noise in the mining area due to items such as heavy equipment operation and drilling and blasting to remove overburden. Some of the loss or damage of habitat in a coal mining operation can be mitigated by habitat restoration due to efforts to reestablish vegetation on areas once mining is complete. However, such restoration efforts often favor elk due to the fact that grasses and forbs are much easier to reestablish on mined areas than woody shrubs needed during winter by mule deer and pronghorn antelope.

The cumulative impacts of all of the activity associated with various types of energy development across the landscape can have a large impact on wildlife. Natural gas fields and coal surface mines can extend over large segments of habitat across the areas in question. If this becomes the case, man-made habitat fragmentation will occur. Habitat fragmentation has two primary components; (1) loss of natural habitat type(s) within a larger landscape and (2) division of the remaining natural habitats into isolated patches (Wilcove et al. 1986 and BLM 2003). Effects of habitat fragmentation on biological resources can include but are not limited to the following:

- (1) Elimination of species or individuals that occurred in habitat patches that are lost (Noss and Csuti 1994 and BLM 2003).
- (2) Isolation of remaining habitat patches by formation of migration barriers (Noss and Csuti 1994 and BLM 2003).
- (3) Crowding of species or individuals into remaining patches followed by declines in population density (Lovejoy et al. 1986 and BLM 2003).

While habitat fragmentation can occur naturally, the faster time scale for man-made fragmentation is a serious concern.

Big Game Data Collection

Wildlife managers collect a variety of data in order to manage big game herds. Following is a generic discussion of the types of data collected, methods used to collect data, reports generated

and a description of how the data is used in the big game management process. Discussions about how Montana and Wyoming each collect big game inventory and use the information to evaluate big game herds are included in separate sections for the respective states.

Age and Sex Composition Surveys

Age and sex composition surveys (A&SCS) are not attempts to obtain a total count of the number of animals in a herd unit (census) or an index to the number of animals in a portion of a herd unit (trend count). Instead it is an attempt to determine the relative number of animals by categories of age and sex that exist in any big game herd. As animals are observed in a survey they are assigned to one of several categories; males (yearling, young adult or mature adult), females, or young (less than 1 year of age). During an A&SCS observers attempt to collect a sample of animals from a herd unit that is representative of the unit or area, not a total count (McCullough 1993 and 1994). Once the survey is completed, the data is compiled and the results are expressed as ratios of males/100 females and young/100 females. These ratios are then used in the various analyses that biologists conduct as they are evaluating big game herds in preparation for making hunting season recommendations.

A&SCS of big game herds can be obtained by ground or aerial surveys. If aerial surveys are conducted, either fixed-wing aircraft or helicopters can be used, however helicopter surveys usually provide the most accurate information. A&SCS can be conducted at various times throughout the year. For mule deer and elk, these surveys are usually conducted after the hunting season (post-hunt), usually in December for mule deer and in January or February for elk. A&SCS for pronghorn can be conducted before (pre-hunt) or after hunting seasons and both Montana and Wyoming do pre-hunt A&SCS.

Five separate ratios can be estimated from A&SCS; a young/100 female ratio, total males/100 female ratio, mature males/100 female ratio, young males/100 female ratio and yearling males/100 female ratio. For the purpose of these surveys, any female older than a fawn or calf is considered an adult female. These ratios are used by biologists in an evaluation process and provide information about production, recruitment and survival for the various herds (Bender 2006).

Two of these ratios are particularly important as measures of herd health; annual production of young and recruitment of young to the yearling age class. The young/100 female ratio is a measure of the annual production of fawn deer and pronghorn or calf elk at the time of the survey. It is important to note that this is not a true measure of production since some mortality of young animals has likely occurred prior to the time of the survey. Usually, a higher ratio of young/100 females indicates a more productive or healthy herd.

The yearling male ratio is a measure of survival and recruitment of the previous year's young to the yearling age class. Yearling buck deer and pronghorn and yearling bull elk are readily identified in the age and sex surveys by their distinctive horn or antler size and configuration. After a severe winter such as the winter of 1983-84, the pre or post-hunt yearling male ratio following the winter is usually very low. This is an indication of a large loss of young the previous winter and a lack of recruitment of those young to the yearling age class. Conversely, during mild winters, young survival is usually good, resulting in more fawns or calves being recruited to the yearling age class and resulting in higher yearling male ratios. Usually, high yearling male ratios denote good herd health.

Harvest Surveys

Estimates of big game harvest are obtained for all deer, elk and pronghorn antelope herd units or hunting districts with hunting seasons. Harvest estimates are obtained via telephone surveys or mail-in questionnaires of a random sample of licensed hunters. Harvest estimates in units with limited licenses usually have a higher level of precision due to the known universe of hunters. In addition, hunting pressure and success rate information is calculated based on the information

gathered during harvest surveys. Harvest, hunting pressure and hunter success rates are obtained for all seasons, providing information on impacts of different seasons and methods of take on the big game resource. A harvest estimate for males, females and young is usually provided for every unit for which there is a hunting season. Harvest information is an input parameter for any method used to analyze big game herds and it is considered one of the most accurate pieces of information gathered for the purpose of big game management.

Other Surveys

In addition to the above mentioned surveys, additional surveys such as census, survival estimates and radio telemetry are often used to gather additional information about big game herds. It is beyond the scope of this report to provide a detailed discussion of these techniques at this time. If any of these surveys or techniques are utilized by either Montana or Wyoming they will be discussed in the individual state portion of the report.

SECTION II

GREATER SAGE-GROUSE BIOLOGY, ECOLOGY AND MANAGEMENT

Sage Grouse Biology and Ecology [Unless otherwise stated, condensed from Colorado Greater Sage-grouse Conservation Plan (CGSGSC 2008)]

Species Description

Greater Sage-grouse (GrSG) (*Centrocercus urophasianus*), are the largest grouse species in North America and were first described by Lewis and Clark in 1805. They are known for their strong association with sagebrush habitat, using sagebrush for both food and cover at all times of year. There are two species of sage grouse. The greater sage grouse occupy the range that is basically north of Interstate 70 while the smaller and rarer Gunnison Sage Grouse (*C. minimus*) occur to the south of Interstate 70 to Eastern Utah and as the name implies are most common around Gunnison, CO. The 2 species are differentiated morphologically, by size, genetically and behaviorally by differences in strutting behavior and vocalizations. The current ranges of the 2 species do not overlap nor are they contiguous to one another.

Greater sage-grouse adult males weigh between 5.5 - 7.0 pounds while the females are smaller and weigh between 2.9 - 3.8 pounds, yearling males range from 4.9 - 6.2 pounds, and yearling females weigh 2.6 - 3.5 pounds. Males have contrasting white upper breast and black bib at the throat, long black filoplumes at the base of the neck, and 2 yellowish air sacs on the chest, which are most conspicuous when inflated during spring courtship displays.

Food Habits

Sage Grouse differ from other grouse in that they do not have a muscular gizzard. The bulk of their diet consists of vegetation, mainly sagebrush and a few forbs with some insects in the summer. Highly used forbs include common dandelion, prickly lettuce, hawksbeard, salsify, milkvetch, sweet clover, balsamroot, lupine, Rocky Mountain bee plant, alfalfa, and globemallow. For the first 21 days, sage grouse chicks are dependent upon insects for their diet (beetles, ants, grasshoppers). After the chick reach 4 to 8-weeks-old their diet will shift to more plant material (approximately 70% of the diet). Succulent forbs are predominant in the diet until chicks exceed 3 months of age, at which time sagebrush becomes a major dietary component.

From late-fall to early spring the diet of GrSG is almost exclusively sagebrush. Many species of sagebrush may be consumed, including big, low, silver, and fringed sagebrush. Unlike big game species GrSG have been known to gain weight over the winter. During severe winter, sage grouse are dependent upon tall sagebrush that remains exposed above the snow. If this habitat is limited, fat reserves can decrease. On cold winter nights GrSG protect themselves and conserve energy by burrowing down into soft snow banks.

Breeding

Sage-grouse put on an elaborate mating display on open areas or "strutting grounds", more generally referred to as "leks". Lek sites must provide the birds with good visibility that will allow the birds to detect predators such as raptors.

The sage-grouse mating system is polygamous (males mate with several females). Adult males defend territories in successive years and will defend them from rival males. While sub-adult males do not establish territories or mate, they might attend a lek.

Strutting occurs from mid-March through late May, depending on elevation. Males arrive on the leks approximately 1 hour before dawn, and display until approximately 1 hour after sunrise. Females generally arrive later and depart earlier. The females will generally mate with a few dominant males that occupy the best sites on the lek. The males do not provide any other involvement with nesting or rearing the young sage grouse.

Nesting

GrSG generally will select a nest site within 2-3 mile of the lek site where it was bred. Nests are typically shallow bowls lined with leaves, feathers and small twigs placed on the ground at the base of a live sagebrush bush. Females select nest sites with good ground cover (grass and forbs) in addition to the cover provided by the sagebrush. GrSG clutch size ranges from 6 -10 eggs, with 7 - 9 being the most common. Incubation does not start until the last egg is laid and eggs are incubated 27 to 28 days. GrSG have one of the lowest nest success rates of all the upland game bird species. While re-nesting can occur, it is infrequent. When it does occur, it usually results in a smaller clutch size than the original nesting attempt. The first eggs are usually laid in late April with hatching beginning mid-May to July with the peak in mid-June.

Movements, Habitat Use and Seasonal Activity Areas

Depending on the dispersion of habitat across the landscape, this may result in the birds using broad landscapes throughout the year, moving great distances in some seasons, and exhibiting annual migratory patterns. If seasonal habitats are contiguous, the population may not show movement that could be considered migratory. The extent of movement in a given population varies with distribution of cover types, topography, and severity of winter weather.

Summer - Chicks are precocial and leave the nest with the hen shortly after hatching. Females with chicks move to areas containing succulent forbs and insects, often in wet meadow habitat, where cover is sufficiently tall to conceal broods and provide shade. Groups of unsuccessful females and flocks of males follow similar habitat use patterns during late spring and early summer, but are less dependent on wet meadow areas than are females with broods. Alfalfa meadows can serve as important brood areas.

Fall - As fall approaches, intermixing of broods and flocks of adults are common, and the birds move from riparian areas to sagebrush-dominated landscapes that continue to provide green forbs. As late fall approaches, weather events trigger movements to winter areas. The timing of this movement varies, influenced by yearly weather conditions.

Winter - GrSG winter range varies according to snowfall, wind conditions, and suitable habitat. Sage-grouse may travel short distances or many miles between seasonal ranges. Movements in fall and early winter (September-December) can be extensive, sometimes exceeding 20 miles. Flock size in winter can vary between 15 - 100+, many time the flocks contain a single sex. Many, but not all, flocks of GrSG males can over-winter in the vicinity of their leks, and by March they are usually within 2 - 3 miles of breeding areas used the previous year.

Habitat Requirements

Breeding Habitat: Leks (March – mid-May)

Use of lek sites can be very traditional, with grouse displaying in the very same location from year to year. Some GrSG leks in Wyoming and Colorado are known to have been in use since the 1950s. Leks are usually located in small, open areas, adjacent to stands of sagebrush with 20% or greater canopy cover. Openings are usually natural, including alkali flats and meadows within sagebrush, but they may also be created by humans, including (but not limited to) small burns, irrigated pasture, and roads within sagebrush habitat (Connelly et al. 1981)

Lek sites do not appear limiting, but they may vary in amount of escape cover and quality of sagebrush. The size of area needed for males to strut can vary greatly. Lek sites are usually flat to gently sloping areas of <15% slope in broad valleys or on ridges. Lek sites have good visibility and low vegetation structure, and acoustical qualities that allow sounds of breeding displays to carry. The absence of tall shrubs, trees, or other obstructions appears to be critical for continued use of these sites by displaying males. Sites chosen for display are typically close to sagebrush that is > 6 inches tall and has a canopy cover $\geq$ 20%

Breeding Habitat: Pre-laying (late-March – April)

Little is known or understood about pre-laying habitat. It has been suggested that pre-laying sagebrush habitat should provide a diversity of understory vegetation to meet the nutritional needs of females during the egg development period and it has been suggested that the habitat should contain a diversity of forbs that are rich in calcium, phosphorous, and protein (Connelly et al. 2000).

Breeding Habitat: Nesting (April – June)

Good quality nesting habitat consists of live sagebrush (11-32 inches high) with sufficient canopy cover, and substantial grasses and forbs in the understory. Since there are few herbaceous plants ~~are~~ growing in April when nesting begins, residual herbaceous cover from the previous growing season is critical for nest concealment in most areas (Connelly et al. 2000).

Breeding Habitat: Early Brood-rearing (mid-May – July)

Early brood-rearing habitat is found relatively close to nest sites and is typically characterized by sagebrush stands with canopy cover of 10 - 15% and with understories that exceed 15% herbaceous cover. In early summer, the size of the area used by GrSG appears to depend on the interspersions of sagebrush types that provide an adequate amount of food and cover. Females and broods may select riparian habitats in the sagebrush type that have abundant forbs and moisture. Females with broods remain in sagebrush uplands as long as the vegetation remains succulent, but may move to wet meadows as vegetation desiccates. Depending on precipitation and topography, some broods may stay in sagebrush/grass communities all summer while others shift to lower areas (riparian areas, hay meadows or alfalfa fields) as upland plant communities desiccate.

Summer – Fall Habitat (July – September)

As sagebrush communities continue to dry out and many forbs complete their life cycles, sage-grouse typically respond by moving to a greater variety of habitats, and generally more mesic habitats. This is the period of time when GrSG can be observed in atypical habitat such as farmland and irrigated habitats.

From mid-September into October, GrSG prefer areas with more dense sagebrush (>15% canopy cover) and late green succulent forbs before moving to early transitional winter range where sexual segregation of flocks becomes notable. During periods of heavy snow cover in late fall and early winter, use of mountain and Wyoming big sagebrush stands is extensive.

Winter Habitat (October-February)

GrSG winter habitat use depends upon snow depth and availability of sagebrush, which is used almost exclusively for both food and cover. Used sites are typically characterized by canopy cover >25% and sagebrush >12 - 16 inches tall and are associated with drainages, ridges, or southwest aspects with slopes < 15%.

During extreme winter conditions, GrSG will spend nights and portions of the day (when not foraging) burrowed into “snow roosts”.

Distribution

Wyoming and Montana are in the heart of the current GrSG range-wide distribution in fact Wyoming has the largest population and Montana has the second largest population of GrSG. WFGD (2003) reports that more than half of the 62 million acres of habitat in the state are dominated by sagebrush (32 million acres). Some populations, such as in Nebraska, were historically very limited in distribution and have since been extirpated. Although GrSG distribution within Montana and Wyoming has diminished, the loss of range has been substantially less than in a number of other states, including Idaho, Oregon, and Nevada.

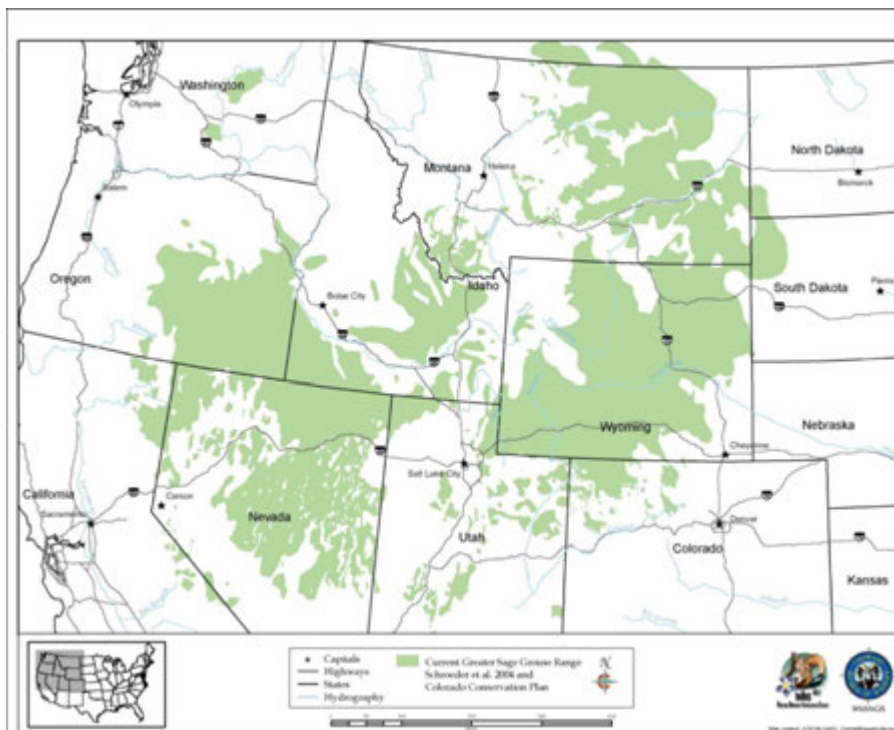


Fig. 3. Map showing the current range of Greater Sage-grouse

A closer view of the Montana and Wyoming GrSG range indicates that some GrSG populations cross state and international borders. This is not surprising and it does underscore the need for agencies to coordinate population and habitat management efforts across state and international boundaries that are responsible for the apparent discontinuities in distribution that occur along borders.

Factors Influencing Sage Grouse Populations

There are many factors that influence sage grouse populations. Some are positive and some are negative. Below is an alphabetical list of some of the major factors that have an influence on GrSG.

Agricultural Conversion

Thousands of acres of sagebrush lands in MT and WY have been converted to agricultural lands. Sagebrush habitats are supported by deep soils that are suitable for irrigated and dry land farming.

Vegetation management can be achieved through biological, mechanical, or chemical treatments. Biological treatments include prescribed fire, designed domestic livestock grazing, and insect pathogens. Fire, floods, insects, mammal and bird herbivory, plant diseases and allelopathy (chemical inhibition) are also biological processes. Chemical treatments to manipulate, control, enhance or remove sagebrush include a variety of herbicides and fertilizer. Mechanical brush control treatments in sagebrush systems include mowing, plowing, roto-beating, chaining, disking, roller harrowing, raking, and bladeing. Reseeding and planting shrubs is also common (SCSGWG. 2007).

Deibert (2005) (Fig. 4) listed agriculture as the 4th most significant threat to GrSG out of 19 issues.

Disease and Parasites

There are numerous viral and bacterial diseases of birds that have the potential to affect GrSG. Coccidiosis and tularemia are 2 diseases that have been documented in GrSG and they are uncommon. Most diseases have not proven to be serious problems for GrSG. However, West Nile Virus has been a recent problem that has negatively affected sage grouse. It is spread by mosquitoes and has rapidly spread across the entire country. Another viral, mosquito borne disease, Avian Pox has a potential to negatively affect GrSG. GrSG are known to have a full host of known internal and external parasites but none are known to cause major problems.

West Nile virus is a relatively new phenomenon affecting sage-grouse with the first mortality documented in 2002 in the Powder River Basin, Wyoming. Researchers monitoring radio-collared sage-grouse have provided the most insight on prevalence and mortality rates given that mortalities are more likely to be found and in a more timely manner. Weather conditions play a large role in West Nile virus outbreaks as high temperatures are necessary for the primary vector, the *Culex tarsalis* mosquito, to produce in large numbers and amplify the disease. A second factor is mosquito breeding habitat which can develop from precipitation filling natural or manmade wetlands or ponds. Reservoirs constructed to hold water produced from coal bed methane natural gas (CBNG) production greatly increased the amount of mosquito breeding habitat in the Powder River Basin. Biologists found lower West Nile virus infection rates outside of coal bed methane natural gas (CBNG) fields. The disease was present each year of the study and reduced annual female survival rates 0-27% and reduced estimates of population growth 7-10% per year. Biologists suggest eliminating manmade water sources that provide mosquito breeding habitat could reduce disease occurrence (NEWLWG 2014).

A population viability analysis of the Powder River Basin population concluded that the low elevation population in northeastern Wyoming is most threatened by West Nile virus (Taylor et al, 2012a). An outbreak year is predicted to decrease the area lek counts by 60% due to an increase in lek extirpations. In all likelihood, West Nile virus will continue to be a factor in sage-grouse ecology resulting in extirpation of population segments during outbreak years. The interaction of energy development and disease compound the threat to sage-grouse with the development of water retention ponds creating habitat for breeding mosquitoes. The combination of a small population, intensive energy development, vulnerability to West Nile virus and other potential stressors (i.e. weather, wildfire) increases the likelihood for lek extirpation.

Energy Development and Mining

Energy and mineral deposits occur throughout much of the known range of GrSG in MT and WY and pose a potential for direct conflict with the birds and their habitat. Due to a lack of control/treatment experiments, there is uncertainty regarding the potential impacts. Some of the

issues and potential conflicts could result from the development of coal (underground, strip mining and coal bed methane development), wind farm development, and oil and gas.

The potential risks to GrSG from energy development can be summarized in 5 broad categories (CGSGSC 2008):

- 1) Direct Disturbance, Displacement or Mortality
- 2) Direct Habitat Loss
- 3) Increase in Predation
- 4) Increase in Invasive Plant Species and Habitat Quality Decline
- 5) Cumulative Landscape-level Impacts of Energy and Mining Development

Naugle et al. (2006) reported preliminary results suggesting sage-grouse in the Powder River Basin are impacted by intensive CBNG development based on lek monitoring data from 2000 to 2005. Leks within CBNG development had lower population indices than leks outside CBNG development. Inactive leks and leks with lower male counts were usually found within CBNG development. Leks within CBNG fields surveyed during the 2004 and 2005 breeding seasons had 20 males or less while leks adjacent to CBNG tended to have >20 males. Additional analysis of wells, powerlines and leks showed that active leks were twice as far from wells and were 1.5 times as far from power lines when compared to inactive leks. Areas with active leks had one-third the density of wells, one-half the density of power lines, and generally have fewer wells and power lines within 2.0 miles of the lek complex than inactive leks. An additional analysis demonstrated sage-grouse avoidance of CBNG developments that were located in suitable habitat.

Wind energy development, unlike drilling for oil & gas, has no “life-of-project”. The production impacts will continue indefinitely, with periodic disturbance to replace or upgrade turbines and towers and the maintenance of transmission facilities. Wind energy access roads will need to be retained indefinitely for maintenance, and periodically improved to allow access for activities described above. For the reasons described above, there will be no “final reclamation” of a site. Surface disturbance is essentially permanent. In addition, more research is needed to determine if low frequency sound may or may not affect sage-grouse.

Deibert (2005) (Fig. 4) Speculated that oil and gas development as having the greatest threat to GrSG in the eastern portion of their range (CO, WY, and MT). This should be considered a huge effect on the total population of GrSG since WY and MT have the two largest known populations.

Fire in Sagebrush Habitats

Fire, both wild and prescribed burns, can be a double edged sword for GrSG habitat. The effects can be variable due to site differences in sagebrush species, moisture regimes, size/shape of burns, and existing limiting factors for the local GrSG population.

In the short term, fire can remove sagebrush overstory and stimulate grass and forb production that can be beneficial to brood rearing habitat. In the long term, sagebrush can be slow to recover (>20 years+). If the burn is too large or it occurs in the undesirable areas of the habitat such as in prime nesting and winter habitat, the affects can be negative.

Additionally, when any large scale disturbance occurs, the chance of a serious noxious weed invasion can occur and can be difficult if not impossible to remedy. Many thousands of acres of sagebrush habitat in the West have been destroyed by invasion of non-native cheatgrass, Japanese brome and other invasive plants. Cheatgrass is a fire dependent species that thrives when it is burned frequently. Sagebrush on the other hand has a natural fire regime of 35-450 years (Baker 2006). Frequent fire can remove sagebrush seedlings and seed sources as well as other native grasses and forbs that can allow the noxious weeds to be self-perpetuating. Extreme caution must be used prior to a prescribed burn and immediate and appropriate action should be taken to reclaim an area after a natural fire. Priority should be given to using native species for reclamation.

The use of fire and other treatments for improving habitat should be evaluated carefully prior to implementation because removal of large tracts of sagebrush is detrimental to sage-grouse populations. While some birds may be able to adjust by using adjacent sagebrush habitats, sage-grouse hens show fidelity for nesting in the same general area. Mosaic patches of sagebrush of different ages and structures benefit sage-grouse. Vegetation treatments influence the abundance and diversity of insects in sagebrush ecosystems, but the use of vegetative treatments requires planning and understanding of the sagebrush ecosystem so that sufficient stands of desirable sagebrush remain. Treated stands should provide adequate cover and food for the appropriate seasonal habitats and juxtaposition within the area being treated (SCSGWG. 2007).

Genetics

Small isolated populations can suffer from three genetic risks: inbreeding depression, loss of genetic variability and increased mutations. This problem is probably not a big concern for the MT and WY since this area is the largest, contiguous GrSG population area in the eastern part of the GrSG range (CO, WY & MT).

Grazing

Similar to fire, grazing by domestic livestock and wildlife is a complex issue and can have negative, neutral and positive benefits to the sagebrush ecosystem and GrSG. Potential impacts of herbivory on GrSG and their habitat can include:

- 1) Long-term effects of historic overgrazing
- 2) GrSG habitat changes due to herbivory
- 3) Direct effects of herbivory such as trampling of eggs and nests
- 4) Altered use of habitats by GrSG due to the presence of herbivores
- 5) Impacts of GrSG behavior due to structures associated with grazing e.g. fences and windmills

It is difficult to assess the long-term impacts of historic grazing on GrSG and their habitat from the late 1800s to early 1930s and prior to more controlled grazing under the passage of Taylor Grazing Act. During this period livestock stocking rates were at their peak along with assumed high GrSG populations. What is known is that stocking rates and grazing management systems are much lower and more favorable today. The authors speculate that some of the damage done during this period such as severe soil erosion and deeply incised streams could have significantly altered the general productivity of the sagebrush habitats. The loss of many wet meadow complexes, lowered water tables and diminished soil productivity, due to erosion, across large landscapes has and will continue to have a negative effect on GrSG for hundreds of years. This is especially true of areas that have steep topography or drainages that are prone to flash flooding and soil erosion.

Grazing can improve wet meadow and riparian areas by removing dense standing/decadent organic material. Grazing can improve lek sites by reducing overall visibility and vegetative ground cover. Grazing can alter the structure and composition of sagebrush and grass/forbs components. This can be positive or negative depending on the existing habitat conditions and what treatments are needed to enhance the habitat for GrSG.

Grazing can be detrimental if too much of the grass/forb understory is removed. This can result in increased predation to GrSG and their nests and this is a major problem and concern. Chronic overgrazing will eventually increase the sagebrush overstory resulting in further loss of desirable forbs and grasses necessary for chick rearing and hiding cover. Loss of the understory component will result in increased soil erosion and loss of site productivity.

Today, grazing is much more controlled and regulated. The effects, both positive and negative, can vary due to stocking rates, moisture regimes. Livestock grazing and can be a limiting factor for local GrSG populations. What is needed are site specific grazing management plans.

Fragmentation

Fragmentation has been defined as the breaking up of a large parcel of habitat into smaller and smaller pieces. Habitat is a function of three factors: quantity, quality and configuration or juxtaposition (how the various habitat components, that are necessary for the survival of the species, are arranged across the landscape). Fragmentation can negatively affect all of these components. Major causes of fragmentation in the sagebrush community could include agricultural conversion, fire, oil and gas development, housing developments, roads, wind farms and strip mining. When it comes to habitat requirements for GrSG, large areas are very important and more is better than less. While the overall quality of habitat may not be significantly altered by fragmentation, such as building an interstate highway through the middle of a large block of habitat, this can result in the inability of wildlife to access necessary habitat components that are now isolated on the other side of the highway. A prime example could be a mule deer herd having to cross a major highway to seasonally access their winter and/or summer ranges. Oil and gas developments with high density well spacing, $\geq$ one well per 40 acres, on GrSG habitats has the potential to seriously impact all three of the essential habitat components. Quantity can be lost due to direct loss of habitat by the conversion of sagebrush lands to roads, pipeline, overhead power-lines and drill pads. Quality can be lost due to degradation of the overall habitat by soil erosion and invasion of noxious weeds. Essential habitat components could be destroyed by building a road, drill pad or wind turbine on a major lek. The habitat could be destroyed or diminished if essential components are not close enough together such as important brood area (wet meadow complexes) being too far away from nesting areas that allow safe passage of hens with young chicks.

Housing Development

Housing development will result in the direct and permanent habitat loss, fragmentation and degradation of wildlife habitat. Other direct and indirect losses can occur due to roads, power lines, increased recreational use, noxious weed invasion and associated infrastructure. Colorado has experienced the third highest population growth of any state from 1990-2000 (CensusScope 2006). Conversely Wyoming has fared much better in this category and only increased its population by 0.09% or 40,195 people in the previous decade. Montana population has increased 9.7% from 2000 to 2010 (989,415 people in 2010). Montana is ranked the 48th most densely populated state 6.86 people per sq. mi. and Wyoming is ranked 49th with 5.8 people per sq. mi. and 563,626 people in 2010 (2010 U.S. Census). The Montana and Wyoming Game and Fish Dept. (WG&F) attempts to work with counties to identify and mitigate these impacts to habitat but the effectiveness of these programs vary by the needs and desires of the counties. A recent trend to protect more land in perpetuity by conservation easements is easing this threat.

Hunting

Prior to the early 1900s most of the hunting in Montana and Wyoming was unregulated, subsistence hunting. Around the turn of twentieth century the states of Montana and Wyoming began to regulate the hunting of wildlife. Aldo Leopold, the father of modern wildlife management, ushered in some new ideas and concepts of regulated or sport hunting (Leopold 1933) and modern hunters essentially became the protectors and guardians of huntable wildlife species. Modern wildlife management has been responsible for the successful recovery of many depleted species such as mule, white-tailed deer, elk, pronghorn and many species of small game such as turkey. The underlying principle of modern sport hunting is that hunting mortality is compensatory vs. additive. Research has shown that natural mortality will occur every year whether or not the species are hunted or not. In some cases, regulated hunting can thus "compensate" for some of this natural loss versus "adding" to it. In the case of most big game species, the maximum carrying capacity of the habitat should not be exceeded or habitat damage will occur due to over-grazing. The limiting factor for most big game species in the West is the amount of winter range. This is not usually the case for GrSG that been shown to even gain weight during the winter and their food, sagebrush, is usually not limited.

Small game species such as sage grouse do not directly impact their habitat as do big game species. Also, the question as to whether hunting sage grouse is additive or compensatory is

less clear with evidence supporting both sides of the issue. In recent years, Montana and Wyoming have adjusted their seasons to this concern by closing many marginal areas to sage grouse hunting and/or limiting bag limits, and season lengths in other areas that still support sage grouse hunting.

Deibert (2005) (fig. 4) speculated that hunting is the 3rd lowest potential threat to GrSG on a list of 19 issues .

Herbicides and Pesticides

Herbicides, such as 2-4D and Tebuthiuron (commonly known as Spike), have the ability to alter the total plant community of a habitat (grasses, forbs and shrubs). During the past 50 to 60 years, it was a rather common practice to spray large blocks of sagebrush to increase grass production for livestock grazing. This practice can be detrimental to GrSG and at least on public lands is used more sparingly today.

Similar to fire as a tool to improve GrSG habitat, herbicides can have a negative, neutral or positive benefit to the habitat. This will depend on the present habitat condition and trend, the type of herbicide used, application rate, and timing of the application. Herbicides can alter the horizontal and vertical structure and composition of the plant community. They can also be used to control noxious weeds but at the same time can remove desirable forb and shrub species. Caution should always be used when using this tool. A good understanding of what the desired habitat condition you are trying to achieve is needed and as well as an understanding as to how will the herbicide works to bring about this change. Mistakes can be huge and long-term. Small test plots or trial areas should always be treated first and evaluated prior to initiating large scale projects.

Pesticides may negatively impact GrSG by removing essential insects that are necessary for good brood rearing habitat and improperly used and applied pesticides can be fatal to grouse. As mentioned earlier, the arrival of West Nile virus in the GrSG range presents a known risk to grouse from this disease. In this case, the safe use of proper insecticides to control mosquitoes might be beneficial to GrSG as well as draining anthropomorphic water sources that allow mosquitoes to breed.

Pinion-Juniper and conifer Encroachment

Pinion pine, juniper trees are commonly referred to as P-J. P-J and other conifer have been slowly creeping into some sagebrush steppe communities since the late 1800s. Miller and Rose (1999) hypothesized that three factors were contributing to this change: 1) a mild and wet climate period during the period 1870-1920; 2) introduction of domestic livestock; and 3) a reduction in the fire intervals. Prior to 1880 natural fire played an important role in ridding sagebrush-steppes of invading P-J. Domestic livestock have been responsible for removing much of the finer fuels in the understory. This can prevent the spread of fire and protect young P-J seedlings. Also, grazing removes some of the competition from the understory of grass and forbs and therefore further benefits the encroachment of P-J.

P-J and conifer encroachment degrades sage grouse habitat and the birds are known to avoid areas with lots of P-J and conifers. Some have speculated that this is probably due to loss of visibility and the potential for increased raptor predation due to more and better raptor perches, etc.

Removing invading conifers, pinion pine and juniper trees in sagebrush communities is usually a high priority habitat treatment objective for most sage grouse ranges and one that does not usually generate a lot of controversy and is usually always beneficial to GrSG.

Predation

Predation has been determined to be a major threat and cause of mortality to sage grouse populations (Connelly et al. 2000). Major predators of adults and juveniles include many types of raptors, great-horned owls as well as mammalian predators such as coyotes, red fox, bobcat and weasels. Predation of eggs can be a serious problem from crows, ravens, magpies, northern harriers, badgers, ground squirrels, raccoons, red fox, skunks, snakes and even elk.

Predator ecosystems are very complex. For example, reducing the density of coyotes in an area can result in an increase in red fox that are more efficient predators of sage grouse and their nests. Habitat degradation and fragmentation also can be a major contributor to high predation rates. Degraded habitats can have less understory cover that makes grouse more vulnerable to predation. Fragmented or linear habitats can improve predator efficiency to the demise of the prey species.

In 2014, Idaho secured a permit from the USFW to kill as many as 4,000 ravens over two years near Idaho National Laboratory in Arco, the Curlew National Grasslands and in Washington County near the Oregon border. Sage grouse populations have declined more steeply in those areas than elsewhere in the state. The Idaho Fish and Game hopes to kill the ravens by placing poisoned chicken eggs in strategic locations. The poison, DRC-1339, is supposedly only kills birds of the Corvid family, such as crows, ravens and magpies. The jury is still out on whether or not this program will be beneficial to GrSG.

Recreation

Human outdoor recreation can negatively impact wildlife such as sage grouse. Dispersed recreational activities such as off-road vehicle use, hiking, cross country skiing, mountain biking and horseback riding have all increased dramatically in recent years. Wildlife viewing has a potential to negatively impact wildlife since people will sometimes approach wildlife to get a closer look or take a better picture. Direct impacts to GrSG can include flushing birds away from lek site or nest, elevated heart rates and stress, expending fat reserves in critical winter situations, separating broods from adults or abandonment of nest, etc. Numerous wildlife disturbance studies have shown that the biggest response is elicited from humans on foot and this is exacerbated when humans are accompanied by dogs. If the dogs are free ranging or off the leash the potential to disturb wildlife is even greater.

Roads

Roads can have multiple impacts on terrestrial wildlife including 1) increased mortality from direct collisions; 2) changes in behavior; 3) loss or degradation of habitat; 4) spread of noxious weeds; and 5) increased human access resulting in greater human interference (Jackson 2000).

Holloran (2005) reported that GrSG males on leks within 1.8 miles of main haul road declined significantly relative to the number of males on control leks located >3.7 miles from main haul roads.

Many authors have reported on how roads facilitate the spread of noxious and invasive weeds. Road construction and the resulting disturbed soils can open up the environment to allow the establishment of weeds. Weed seeds can hitchhike on vehicles or be hauled in with loads of gravel or fill dirt. Once they are established along the road corridor, sometime many miles from other known seed sources, the spread to other pristine areas can occur rapidly due to a large scale disturbance such as a fire.

Increased access can facilitate increased human use and recreation. If the animals in these areas are subject to hunting pressure, they can learn to avoid areas near roads and become concentrated in more remote areas and thus decrease the overall size of their occupied range.

Roads are notorious for causing fragmentation of habitat. This can have a negative effect on species such as GrSG that require large, undisturbed blocks of habitat.

Weather

Severe winters such as the winter of 1983-84 are believed to have been a factor in the decline of GrSG. Deep snow, high winds and very cold temperatures may have contributed to more stress and higher mortality. Packed and crusted snow could have prevented the birds from burrowing into the snow for thermal protection. Deep and drifted snow covered winter foraging areas and added additional stress to the wintering birds. Late spring storms can increase mortality of newly hatched GrSG chicks.

Spring and summer droughts can diminish the production of forbs and insects essential to young GrSG chicks and reduce residual understory vegetation needed for nesting cover the following year. Dry hot summer can stress young chicks and decrease survival rates.

Weeds

Noxious and invasive weeds are a serious threat to rangeland health and can degrade habitats, by increasing fire frequency, decreasing plant diversity, changing the structure of plant and insect communities and reducing the quantity and quality of palatable forage. Noxious weeds occur in much of the GrSG ranges in MT and WY. Annual noxious weeds such as cheatgrass in sagebrush ecosystems can increase the mean fire return interval to 5-10 years vs. 20-100 years in natural sagebrush ecosystems (Miller and Eddleman 2000). More frequent fires can prevent the re-establishment of native grasses, forbs and shrubs such as sagebrush. Cheatgrass is a major problem in the drier and lower elevation sagebrush ranges. Noxious weeds have a competitive advantage over native plants and if left unchecked can proliferate and form large monocultures of weeds that reduce forage palatability and can seriously degrade habitats. Noxious weeds are a common occurrence whenever there is any ground disturbance activity such as road, housing development, oil and gas, etc. Invasive plants are spread in many ways: seeds falling from vehicles and machinery, carried by birds, animals, humans, wind, water, livestock feeds, and some have been imported and planted originally as ornamental plants. Each county in MT (<http://mtwow.org/weed-laws.htm>) and WY (www.wyoweed.org) has an official list of noxious weeds.

Deibert (2005) (Fig. 4) speculated that invasive weeds were the number one threat to GrSG across their entire range and the 3rd highest threat to GrSG in the eastern portion of their range (CO, WY, & MT).

Wyoming Fish and Game Dept. (2003) reported that the most serious noxious weeds to GrSG are knapweed, leafy spurge, cheatgrass and Japanese brome.

Threats Summarized by Endangered Species Act (ESA) Listing Process

Determining and analyzing the threats to GrSG is a complicated and tedious process that is undertaken whenever the federal government is petitioned to review the status of a species under the ESA. The results of this process can reveal some detailed analysis of the potential threats and how they might affect the species. For this reason, the following discussion is included to further understand the threats to GrSG:

The ESA analyzes the need as to whether to list a species or not and the process can reach 1 of 4 conclusions: **threatened, endangered, not warranted or warranted but precluded**. This process is decided based upon 5 limiting factors:

- 1) The present and threatened destruction, modification, or curtailment of the species' habitat or range.
- 2) Over-utilization of the species for commercial, recreational, scientific, or educational purposes.
- 3) Disease or predation affecting the species.
- 4) The inadequacy of existing regulatory mechanisms to protect the species.
- 5) Other natural or manmade factors affecting the species' continued existence.

On January 12, 2005, the U.S. Fish and Wildlife Service (USFWS) (USFWS 2005) published a “not warranted” decision for the GrSG, meaning that the bird will not be listed as a threatened or endangered species. The USFWS reviewed volumes of data concerning GrSG, sagebrush ecosystems and the potential threats to both. Despite the volumes of data, substantial gaps and uncertainty remain in the scientific community’s knowledge of all the factors that may affect GrSG populations and their habitats across a wide geographical range.

The USFWS (2005) concluded that none of the threats listed in the five listing factors was significantly affecting current numbers of GrSG. They did however, specifically mention that sagebrush habitat continues to be lost and degraded in parts of its range, but at a lower rate than that historically observed.

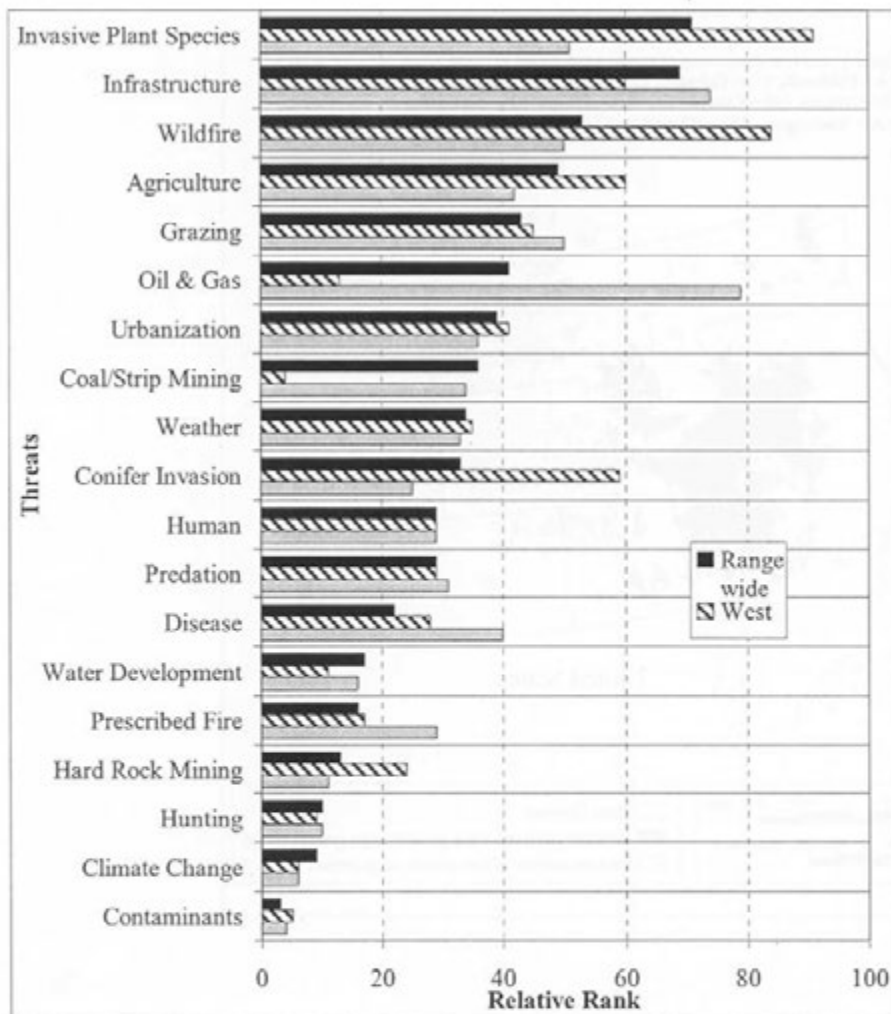
Figure 4 depicts the relative impact of each threat to the species (as determined by an expert panel) in 3 different aspects of GrSG range: 1) the entire range; 2) the east portion of the range; and 3) the west portion of the range (which includes MT and WY).

After the Jan. 12, 2005 finding of not warranted, the Service continued to receive petitions to list GRSG. On 5 March 2010 the U.S. Fish and Wildlife Service announced its 12-month finding on a petition to list the greater sage-grouse (sage-grouse) as threatened or endangered under the Endangered Species Act (ESA). The Service found that the sage-grouse is **warranted, but precluded** by higher priority listing actions. The Service identified two threats which contribute to the vulnerability of healthy and sustainable sage-grouse populations;

- 1) The present or threatened destruction, modification, or curtailment of the habitat or range and
- 2) The inadequacy of existing regulatory mechanisms.

The warranted, but precluded finding resulted in the sage-grouse becoming a “**candidate**” species for listing which requires the Service to conduct an annual status review.

In February 2012 a federal court judge rejected a challenge from environmental groups to force the U.S. Fish and Wildlife Service to list the sage-grouse as threatened or endangered. However, another federal court settlement requires the U.S. Fish and Wildlife Service to review the candidate status of 251 species, including the sage-grouse, to determine if they warrant the full protection from the Endangered Species Act or should be removed from the candidate list. The deadline for the decision on the sage-grouse is the **end of fiscal year 2015**.



Key: ■ = Rangewide ▨ = Western □ = Eastern

- Infrastructure includes fences, roads, powerlines, communication towers, and pipelines, developed for any purpose
- Agriculture includes activities primarily associated with farming.
- Grazing includes all activities primarily associated with grazing.
- Weather refers to short time events, including but not limited to late season snowstorms, drought, etc.
- Climate change refers to long-term, permanent weather changes, usually occurring over a period of 100 years or more.
- Conifer invasion primarily refers to pinyon/juniper
- Human refers to an increased human presences in sagebrush ecosystems from recreational, residential, and resource development activities .

Fig 4. List of issues and threats that were identified by the USFWS (panel of experts) in the GrSG listing process (Deibert 2005, USFWS 2005).

These issues were then discussed by a panel of GrSG scientific experts to rank the issue for range-wide, eastern and western ranges of GrSG. It is presented only as a tool to facilitate discussion for GrSG and their habitats. The rankings are large scale and may not be applicable in every situation. Therefore it is important to use local information when planning conservation efforts (Deibert 2005, Fig. 1)).

Sage Grouse Management - Monitoring and Population Estimate Methods

Lek Counts

Basic population inventory data and methodology is fundamental to the management of any wildlife species. Since the early 1950s the preferred method to inventory sage grouse has been the lek count. Patterson (1952) first described this method and he speculated that the maximum number of males counted over 3 or 4 counts spread over the display period might be a useful index or trend to sage grouse populations. The methodology for lek counts has evolved and been modified over time. Autenrieth et al. (1982) and Connelly et al. (2000) urged caution in interpreting the data but lek counts still provided the best index to breeding population size and the most widely used tool to estimate population size.

Four assumptions are made to derive an estimate from a lek count (CGSGSC 2008):

- 1) Percent of leks counted – It is assumed that the percentage of leks counted each year is constant. However, numerous studies have shown that this assumption is false and as the population expands, more core leks as well as satellite leks are formed and vice versa.
- 2) Inter-lek Movements – It is assumed that males will only attend one lek. Several researchers using marked birds have shown this assumption to be false and this will inflate the yearly population number or index.
- 3) Lek Attendance – Population estimates from lek count data are based on the assumption that a constant proportion of males, often 75%, are detected by the maximum of 3 to 4 counts per season. However, there is considerable evidence to suggest that lek attendance is highly variable due to age, social status, weather, body condition and parasite load or disease. Generally, the better physical condition the male is in, lipid and protein reserves, the more likely they are to attend the lek on regular basis and for a longer time period.
- 4) Sex Ratio - Most population projections assume that there are 2 - females/male in the breeding population. Males are assumed to suffer higher mortality than females and thus make a smaller portion of the population. However, numerous studies from wing data (CDOW unpublished report) has yielded sex ratios varying from 1.5 to 1.8 females/male over a long time period which is lower than the usually assumed 2.0 female/male used in most population projections.

Habitat Monitoring

Connelly et al. (2003) provided four basic reasons to assess habitat including: “

- 1) To document current condition and trend of habitat;
- 2) To evaluate impacts of a land treatment;
- 3) To assess the success of a habitat restoration program; and
- 4) To evaluate the ability of habitat to support a reintroduced population.”

All four of the above reasons have a stated or underlying assumption that research will be done to assess current conditions as well as to monitor long-term changes.

Habitat monitoring research has become increasingly important, but has often depended on dramatically variable sets of data, requiring substantial interpretation (Connelly et al. 2004). Unfortunately, despite improving technology, there is still a shortage of established habitat monitoring techniques available to monitor long-term change in habitats. Lacking established protocol, monitoring of habitat will continue to depend on the careful interpretation and painstaking data manipulation necessary to compare disparate sets of data (Connelly et al. 2004, Stiver et al. 2006).

Brood Surveys

Brood surveys are an established technique used in some areas and are designed to provide an indication of abundance and distribution as well as an index of productivity (chicks/female). If the results of brood surveys vary by year, region, weather, date, or observer, it is important that this variation be accounted for and controlled if possible (Stiver et al. 2006). MT does not conduct brood surveys (J. Ensign Persl. Commun.)

Harvest Surveys

Stiver et al. (2006) reported the three most common techniques for monitoring harvest include hunter questionnaires or surveys, wing collections (Braun 2002), and field contact hunter bag surveys. The most traditional technique is the bag survey. By directly contacting the hunter, biologists are able to ask questions, thus obtaining information on harvest rates, success rates, and hunter behavior. Nevertheless, bag surveys are difficult to conduct over a broad area with the consistency necessary to making sweeping assessments of both hunters and the harvested species. Consequently, surveys of hunters by telephone or mail have been used to standardize the survey effort and improve the quantification of the results. Two downsides of questionnaires are that it is difficult to obtain adequate samples of sage-grouse hunters and the harvested birds are not examined. The third technique, wing collection, allows birds to be examined, enough to determine sex and age (Beck et al. 1975), but can be limited with regard to the information collected from hunters and the lack of standardization among hunters and regions. It is for this reason, that wing collections are sometimes combined with other techniques (i.e., mailed in envelopes) so that the quality of the data can be improved.

For all harvest surveys, there is often a lack of information that would provide quantifiable comparisons with other types of techniques (i.e., lek surveys). Consequently, it is difficult to verify the reliability of the results obtained with these techniques. If harvest surveys are going to be used in the future, it is clear that their reliability should be assessed and the techniques improved, if possible. These improvements should include considerations of sample size, stratification, randomization, and repeated measures.

Alternative Methods for Population Estimates

There are several options to estimate GrSG population other than lek counts.

Mark & Recapture Technique – This method requires the manager to capture and “mark” male and female grouse and then count how many of the birds show up at the leks or are “recaptured”. It is assumed that the ratio between marked and recaptured is representative of the entire population, allowing the manager to extrapolate a population projection.

Other methods such as using DNA analysis of fecal pellets found at a lek site may provide an alternative to mark & recapture without actually having to capture and “mark” the birds, an invasive process.

Line-transects, a statistical method that assumes that all of the birds on a transect line are always counted and a lesser proportion are counted as you get further and further from the center line of the transect, could be used to estimate population size. Another alternative could be quadrat census where all the birds are counted in randomly selected blocks and then the population is projected for the whole area. The final estimate needs to be increased due to known sightability errors.

Both MT and WY recognize the shortcomings of the lek count but for the time being this is the best method and the only method that has a somewhat historical basis. Colorado (CGSGSC 2008) makes the following assumptions and recommendations to estimate population size:

- 1) All leks are known and counted (the estimate is thus conservative, if some leks are unknown).
- 2) The maximum of 3-4 counts represents 53% of males in the population.

In order to eliminate one variable (sex ratio), the CDOW and WFGD only estimate the number of breeding males.

The formula that incorporates these assumptions follows:

C = maximum male count on lek

Estimate of males in population = $C / 0.53$

SECTION III

BIG GAME DATA AND ANALYSIS – MONTANA

Montana Fish, Wildlife and Parks uses a variety of methods to evaluate big game herds in order to manage deer, elk and pronghorn antelope in the state.

For mule deer, a process called adaptive harvest management is used for monitoring deer populations, evaluating data and setting hunting season recommendations (MFWP 2001). Adaptive Harvest Management (AHM) has four components; population objectives, a monitoring program, hunting regulation alternatives and modeling. For the purpose of establishing population objectives, the state is divided into 5 ecological types or groups of hunting districts that are known as population management units (PMUs). The PMUs designations are northwest montane, mountain foothills, prairie/mountain foothills, southern mountains and prairie breaks. Each PMU has unique population indicators and a unique monitoring program (MFWP 2001). Information concerning trends in population size, fawn recruitment, fawn and adult mortality, harvest and age structure is collected for each PMU. A series of 13 aerial census and 67 aerial trend areas, representative of environments occupied by mule deer, have been established statewide to facilitate collection of these data. Data collected annually on the survey areas include post-season age and sex composition counts and total count and fawn/100 adult ratio surveys during spring (MFWP 2001). In addition, hunter check stations are used to collect information to monitor the buck segment of deer populations including age, number of antler points and antler size. The area of the state involved in this report, southeast Montana, is included in the prairie breaks PMU. Fixed-wing aircraft are used to collect the information for post-season age and sex composition, spring total count and fawn/100 adult ratio surveys.

The population modeling concept that MFWP uses is very general and not herd specific as compared to population modeling conducted by other state wildlife agencies. Two computer models have been developed, one for mountain deer populations and the other for prairie deer populations. Data from the various census and trend count areas along with different scenarios for hunting regulations and weather can be used to project future conditions for the two major categories of deer populations in the state.

MFWP also relies on the use of trend counts to manage elk herds in the state (MFWP 2004). Trend count areas have been established in nearly all areas of the state that contain elk populations. The trend count areas are flown in winter or early spring, depending on location, and an attempt is made to count all elk in the trend count area. Observers conducting the counts also classify elk to obtain young/100 female ratios and male/100 female ratios. Fixed-wing aircraft are primarily used to conduct these surveys, although helicopters are used to conduct trend counts in areas that are heavily timbered. MFWP is beginning to implement the use of mark/re-sight or sightability correction techniques for most of the surveys on their trend count areas in order to obtain population estimates that more closely represent the actual number of elk in those areas.

MFWP uses the trend count process or technique to manage pronghorn antelope herds in the state and provide data for establishing hunting season recommendations. Trend count areas for pronghorn have been established statewide since 1992 and most are surveyed on an annual basis to produce estimates for population size, herd composition and recruitment. The trend count areas are flown in mid-summer using fixed-wing aircraft to obtain pre-season estimates of males/100 females and young/100 females. The same trend area is flown again in the spring to obtain a total count and young/100 adult ratios. The spring composition count information is compared to the summer count data to provide an estimate of fawn and adult over-winter survival. Data from the total count in the spring is also used to compute a density estimate for the trend count area. The density estimate from the trend count area is then extrapolated to all occupied pronghorn habitat in the hunting district to provide an estimate of total population size.

Montana uses telephone surveys of randomly selected license holders to gather information about harvest for pronghorn antelope. The surveys are designed to provide estimates of total numbers of animals harvested, sex of the animals harvested, numbers of hunters, days of recreation provided and hunter success rates.

Montana does not use computer modeling to evaluate population size and composition of their big game herds as is the case with fish and wildlife agencies in many other western states.

Included below is a map of the area of southeastern Montana that contains the 3 hunting districts for deer, elk and pronghorn for which data were analyzed for this report. Montana uses the same hunting districts for all three species as opposed to Wyoming which uses unique herd units and hunt areas to describe areas occupied by the three big game species.



Fig. 5 Montana hunting districts 702, 704, 705

MULE DEER HUNTING DISTRICT 702 (refer to appendix, tables 31 & 31A)

General Description Mule deer hunting district 702 is located in southeastern Montana and is commonly known as the Yellowstone Pine Hills Hunting District and is the most westerly located of the 3 hunting districts in the study area. The district lies in portions of Treasure, Bighorn, Rosebud and Custer counties. The district is bounded on the north by Interstate Highway 94, on the east by State Route 59 and Route 332, on the south by the Northern Cheyenne and Crow Indian Reservations, on the west by State Route 47. This hunting district, along with hunting districts 704 and 705 an area of approximately 14,378 square miles. Hunting district 702 is the smallest of the 3 hunting districts. Elevation in the three hunting districts varies from approximately 1,970 feet to 4,460 feet. Virtually all of the hunting district 702 is considered to be occupied mule deer habitat.

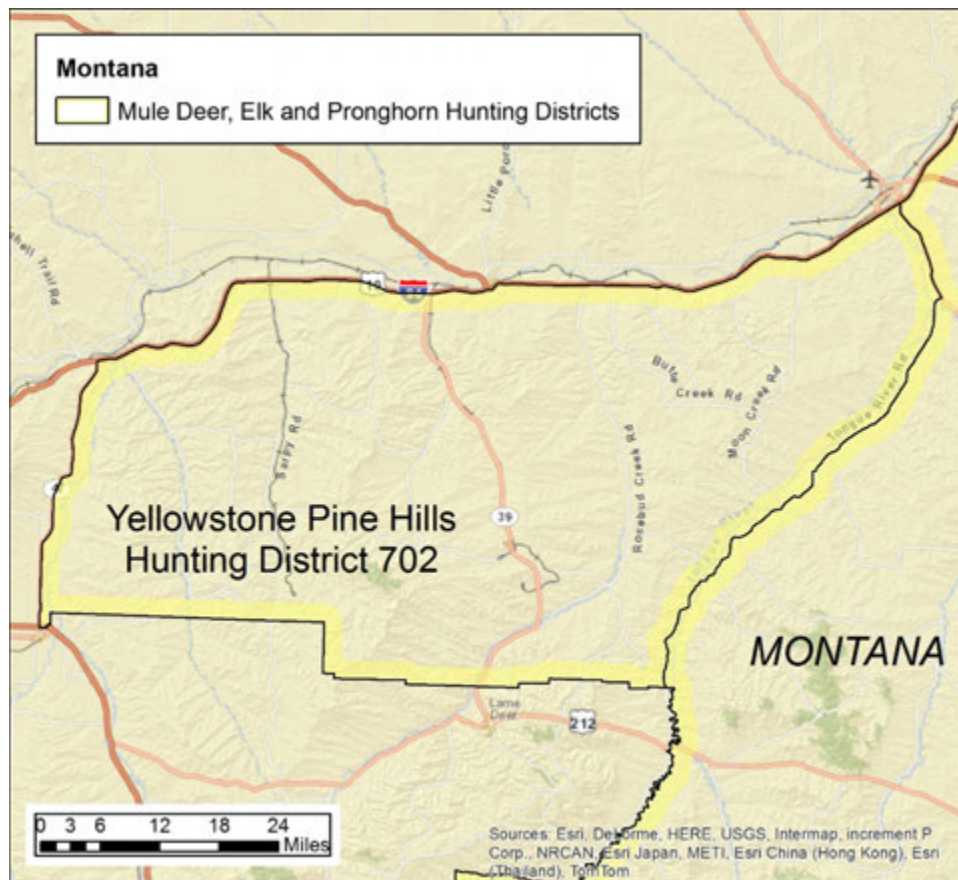


Fig. 6. Montana hunting district 702

The landscape in the hunting district is part of the generic northwest Great Plains eco-region. This main eco-region is further divided into three sub-sections defined as; river breaks, Montana central grasslands and pine scoria hills. The river breaks sub-section is composed of rugged, highly dissected terrain bordering major rivers. Vegetation in this sub-section varies from western wheatgrass and buffalo grass on level bottom lands to threadleaf sedge and needle and thread grass on south facing slopes and junipers and deciduous trees on north facing slopes of drainages. The Montana central grasslands sub-section is a dissected rolling plain studded with buttes and intersected with intermittent or ephemeral streams. Vegetation in this sub-section includes gramma grass, needlegrass and wheatgrass. Pine scoria hills is the third sub-section of the eco-region. This segment consists of stony, rough hills. Vegetation varies from eastern ponderosa pine forest to pine savannah with large patches of grassland. In this hunting district

the percent composition of the various subsections of habitat described above is; river breaks – 5%, Montana central grasslands – 60% and pine scoria hills – 35% (Woods et al. 2002).

Land Ownership Approximately 25% of the area is public land administered primarily by the U. S. Forest Service, Bureau of Land Management and Montana Department of Natural Resources and Conservation. The other 75% is in private ownership (MFWP 2004).

Land Use Much of the private land in the area is used for domestic livestock production. Drilling for coal-bed methane and surface mining for coal are examples of energy development that occurs in the area. Urban and sub-urban development includes the communities of Miles City (pop. 8,646), Harden (pop. 3,505), Colstrip (pop. 2,214) and Forsyth (pop.1,777) (2010 Census Interactive Population Search). The remainder of the human population is in small, unincorporated communities, settlements or individual ranches or home sites throughout the hunting district.

Management Issues Hunting access on private lands is a significant issue that limits deer harvest in some areas of the hunting district. In addition, severe environmental conditions in the form of periodic droughts or harsh winter weather occasionally impacts fawn survival in this hunting district.

Population Size Records for deer population size for this hunting district are incomplete. The estimates for population size are from the Sarpy trend count area that Montana Fish Wildlife and Parks (MFWP) monitors. Data from the Sarpy trend count area indicates that numbers of deer on the trend area have fluctuated from a high of 325 deer in 2000 to a low of 73 deer in 2013. The mean value for numbers of deer observed on the trend area is 153 animals. The long-term trend for deer on the trend count area is decreasing. No long term objective for density or population size has been established for the trend count area.

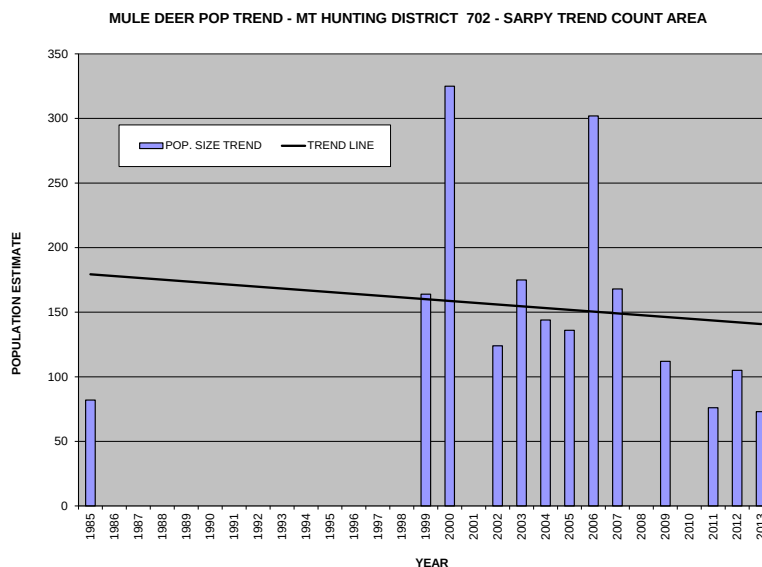


Fig. 7. Mule deer - Montana hunting district 702 – population trend

Age and Sex Composition Male/100 female ratios have varied from a low of 13 males/100 females in 2000 to a high of 49 males/100 females in 2012. The mean value for all years of data is 27 males/100 females. The long-term trend for male/100 female ratios is increasing.

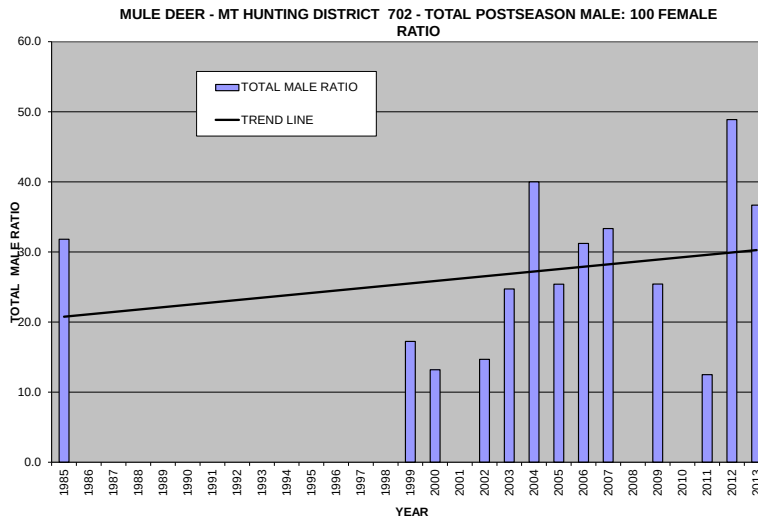


Fig. 8. Mule deer - Montana hunting district 702 - post-season male/100 female ratios

Young/100 female ratios have varied from a low of 45 young/100 females in 1985 to a high of 107 young/100 females in 2013. The mean for young/100 females for the herd unit is 68. The long term trend for young/100 females is increasing.

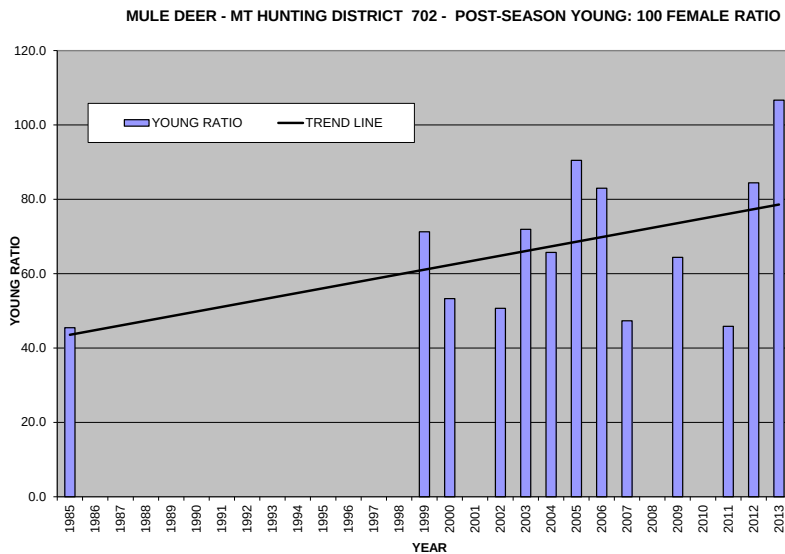


Fig. 9. Mule deer - Montana hunting district 702 – post-season young/100 female ratios

Harvest Male harvest for this hunting district has ranged from a low of 480 bucks in 1981 to a high of 1,855 bucks in 1983. The average for male harvest for all years of the analysis is 1,083 bucks and the long-term trend for buck harvest is declining. Buck harvest by the decade has been steadily decreasing since the 1990s (1,181, 1,042, and 891 animals respectively). The last year that buck harvest met or exceeded the long term average for harvest was in 2004.

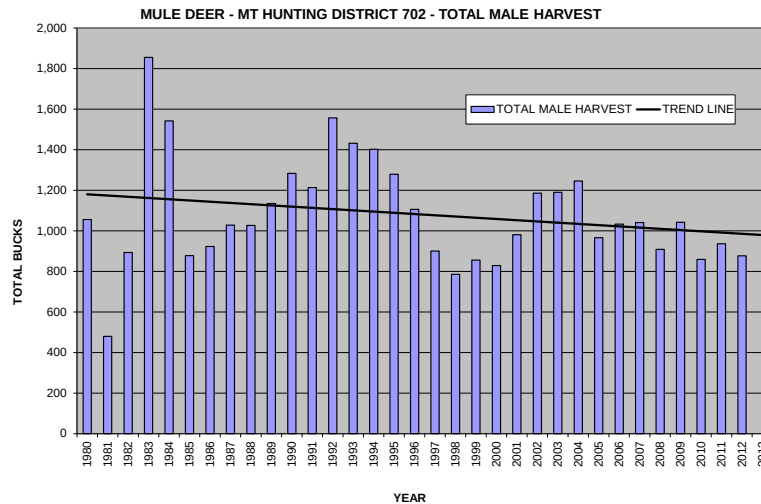


Fig. 10. Mule deer - Montana hunting district 702 – male harvest

Total harvest for this hunting district has varied from a low of 636 animals in 1981 to a high of 5,407 animals in 1984. The mean of total harvest for the period 1980 to 2012 is 1,785 animals. The long-term trend for total deer harvest is decreasing. Since the mid-1980s total deer harvest has never again come close to the total harvest that occurred in 1983. Examining the means of deer harvest by decade reveals a gradual decline in harvest since the 1990s.

Antlerless deer harvest (does and fawns) has taken place in the hunting district every year of the analysis except 1980. In all years that antlerless harvest has occurred it has accounted for more than 10% Of the total harvest and as much as 71% of the total harvest in 1984.

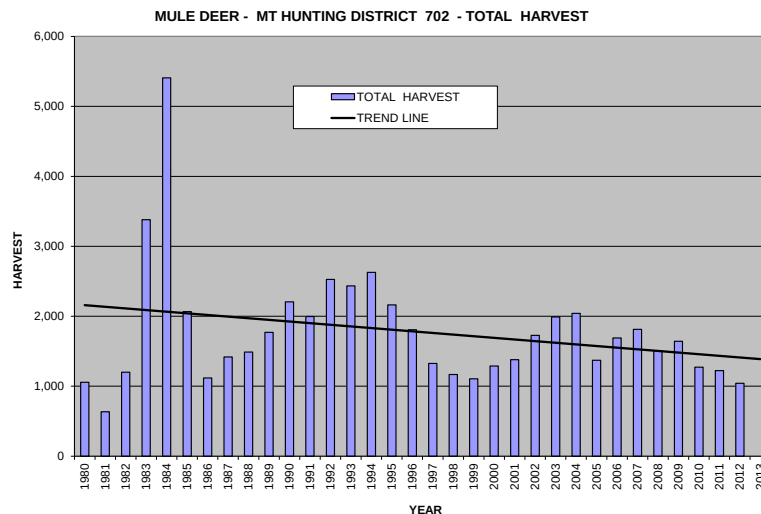


Fig. 11. Mule deer - Montana hunting district 702 – total harvest

Hunter Numbers and Success Rates Total hunting pressure for all seasons and methods of take has ranged from a low of 1,071 hunters in 1981 to a high of 6,059 hunters in 1984. The mean value for hunting pressure for all years of the analysis is 2,656 hunters. The long-term trend for hunting pressure is decreasing. Since the peak in the early 1980s, hunting pressure has remained relatively stable.

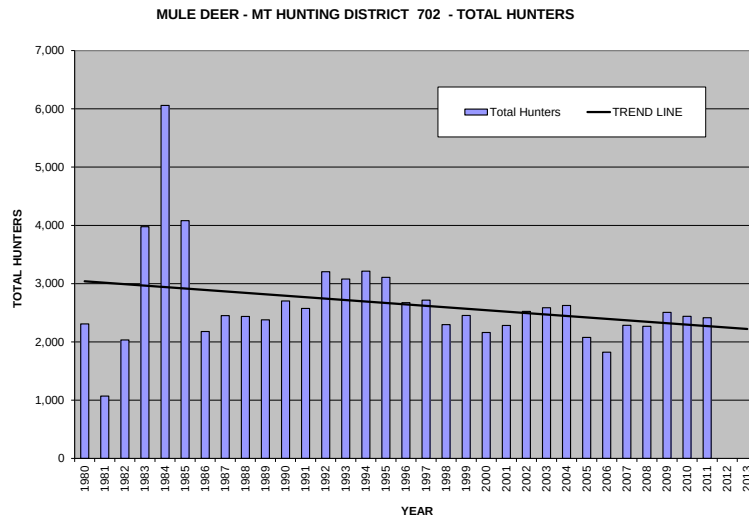


Fig. 12. Mule deer - Montana hunting district 702 – total hunters

Hunter success rates for all methods of take have varied from a low of 45% success in 1999 to a high of 93% success in 2006. The mean value for hunter success for all years of the analysis is 67%. Hunter success in the unit has declined sharply since 2006 to a level nearly equal with the lowest success rates observed in this hunting district, and at 51% success in 2012 is well below the mean value for hunter success of 67%. This is the third such decline that has occurred in the district since 1980.

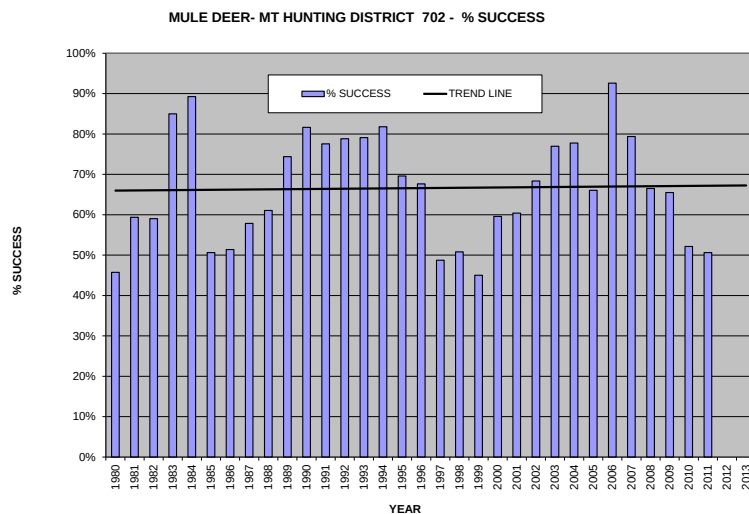


Fig. 13. Mule deer - Montana hunting district 702 – hunter success rates

Summary of Herd Vital Statistics and Management Implications The authors used a combination of information from the literature and our professional expertise and opinions to evaluate big game herd performance. Based on this evaluation each herd was judged to be in either good, fair or poor condition. The authors refer the reader to page 186 for a more thorough explanation of the evaluation process. An evaluation of a variety of data for the mule deer herd in this hunting district indicates that it is not performing at an optimum level. According to the process that was developed for this project, the performance rating for this herd would be fair for the following reasons:

- The long-term trend for population size for the herd is declining. The population for the trend count area that is evaluated for this hunting district is at the lowest level recorded in 12 years of data collection.
- One bright spot in the data is the long-term trend for young/100 female ratios. This trend is increasing, indicating that there is potential for growth in the population.
- However, another negative factor for this deer herd is a decreasing long-term trend for harvest. The total harvest of 1,042 animals in 2012 is the third lowest harvest recorded in the 32 year period of this data analysis. Furthermore, the last 5 years of harvest have been below the long-term mean for harvest (1,785 animals) for this hunting district.

The upshot of all of this information is that if current habitat conditions are maintained, this deer herd will likely show a gradual improvement in population size and harvest. However, if habitat conditions deteriorate due to development or adverse natural environmental conditions, population size, young/100 female ratios and harvest will all likely decrease further than the current situation.

MULE DEER HUNTING DISTRICT 704 (refer to appendix, tables 32 & 32A)

General Description Mule deer hunting district 704 is located in southeastern Montana and is commonly known as the Powder Pine Hills district. The hunting district lies in portions of Bighorn, Custer, Fallon, Powder River, Prairie and Rosebud counties. The hunting district is bounded on the northwest by Interstate Highway 94; on the northeast by O'Fallon Creek; on the east by U. S. Highway 12, the Powder River Road and the Broadus-Moorhead Road; on the south by the Montana-Wyoming state line; on the west by the Crow Indian Reservation, the Northern Cheyenne Indian Reservation, the Tongue River, Route 332 and State Route 59. The hunting district is one of 3 hunting districts, along with hunting districts 702 and 705 that covers an area of approximately 14,378 square miles. Hunting district 704 is the second largest of the 3 hunting districts. Virtually all of the hunting district is considered to be occupied mule deer habitat.

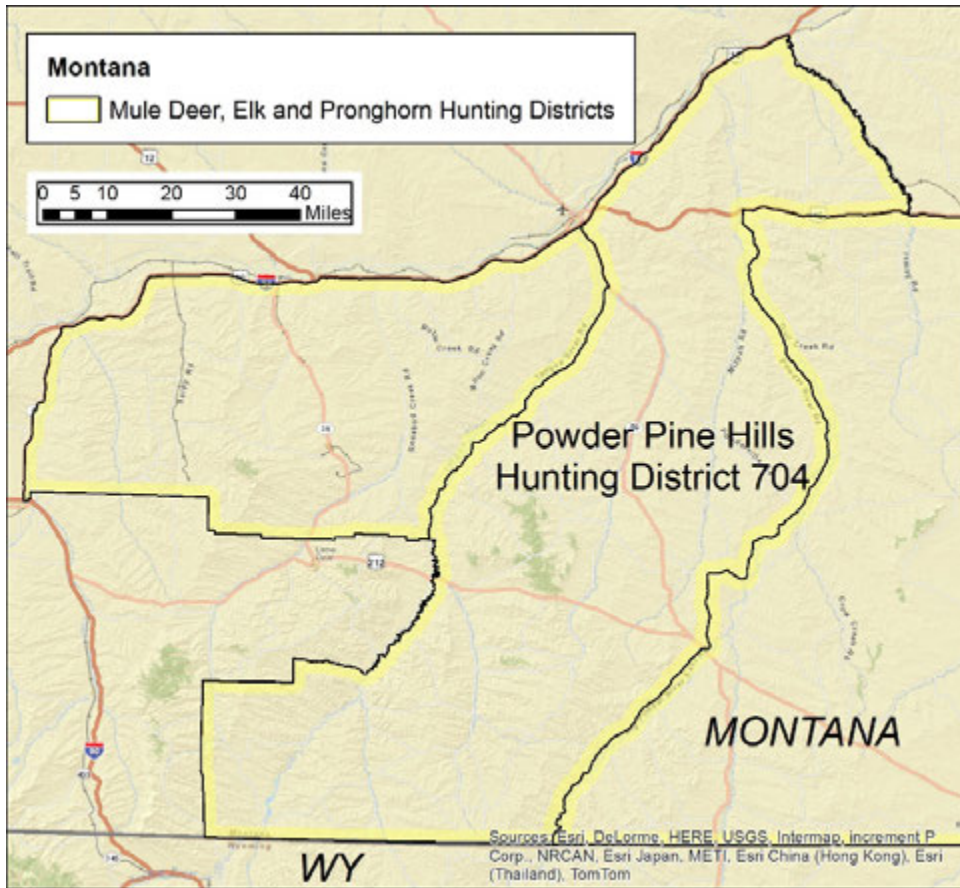


Fig. 14. Montana hunting district 704

The landscape in the hunting district is part of the generic northwest Great Plains eco-region. In this location the main eco-region is further divided into 4 sub-sections designated as; river breaks, Montana central grasslands, pine scoria hills and mesic dissected plain. The river breaks sub-section is composed of rugged, highly dissected terrain bordering major rivers. Vegetation in this sub-section varies from western wheatgrass and buffalo grass on level bottom lands to threadleaf sedge and needle and thread grass on south facing slopes and junipers and deciduous trees on north facing slopes of steep drainages. The Montana central grasslands sub-section is a dissected rolling plain studded with buttes and intersected with intermittent or ephemeral streams. Vegetation in this sub-section includes gramma grass, needlegrass and wheatgrass. Pine scoria hills is the third sub-section of the eco-region. This segment consists of stony, rough hills. Vegetation varies from eastern ponderosa pine forest to pine savannah with large patches of grassland. The mesic, dissected plain sub-section is characterized by a dissected rolling plain. The primary vegetation is gramma grass, needlegrass and wheat grass. In this hunting district the percent composition of the various subsections of habitat described above is; river breaks – 25%, Montana central grassland – 30%, pine scoria hills – 30% and mesic dissected plain – 15% (Woods et al. 2002).

Land Ownership Approximately 25% of the area is public land administered primarily by the U. S. Forest Service, Bureau of Land Management and Montana Department of Natural Resources and Conservation. The other 75% is in private ownership (MFWP 2004).

Land Use Much of the private land in the hunting district is used for livestock grazing, primarily cattle. Drilling for coal-bed methane and surface mining for coal are examples of energy development that has occurred in the area. Urban and sub-urban development includes the

communities of Miles City (pop. 8,646), Broadus (pop. 468), Ashland (pop. 824) and Fallon (pop. 164) (2010 Census Interactive Population Search). The remainder of the human population in the hunting district is in small, un-incorporated communities, settlements or individual ranches or home sites throughout the hunting district.

Management Issues Hunting access on private lands is a significant issue that limits deer harvest in some areas of the hunting district. In addition, severe environmental conditions in the form of periodic droughts or harsh winter weather occasionally impacts fawn survival in this hunting district.

Population Size Records of deer population size for this hunting district are incomplete. The estimates for population size are from the Otter and Olive trend count areas that Montana Fish Wildlife and Parks (MFWP) monitors. Data from the two trend count areas indicate that numbers of deer on the trend area have fluctuated from a high of 1,082 deer in 2006 to a low of 210 deer in 2008. The population size estimate for 2012 is 538 animals. The mean value for numbers of deer observed on the trend area is 524 animals. The long-term trend for deer on the trend count area is stable. No long-term objective for density or population size has been established for the trend count area.

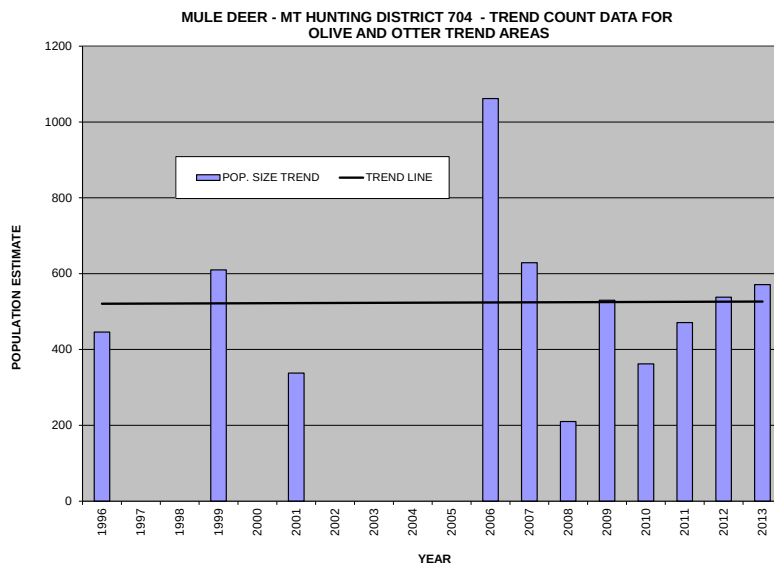


Fig. 15. Mule deer - Montana hunting district 704 – Olive and Otter trend count data

Age and Sex Composition Male/100 female ratios have ranged from a low 0 males/100 females in 2000 to a high of 54 males/100 females in 2006. The mean value for males/100 females for all of the available data is 32 males/100 females. The long-term trend for males /100 females is increasing slightly.

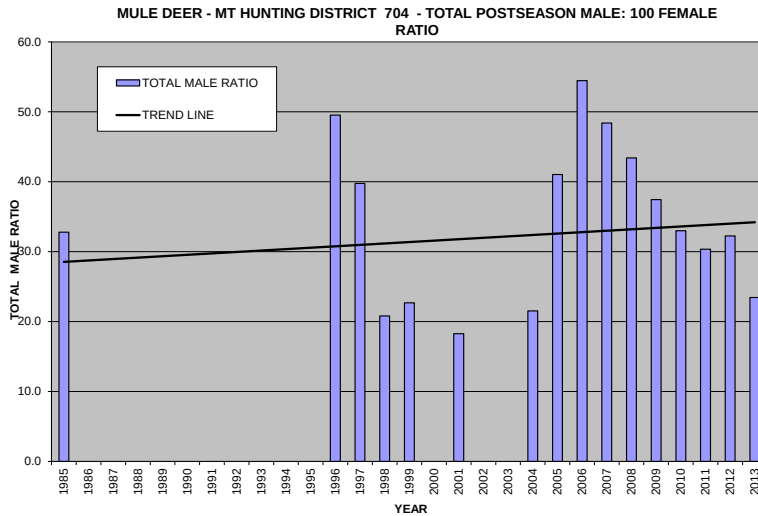


Fig. 16. Mule deer - Montana hunting district 704 – male/100 female ratios

Young/100 female ratios have ranged from a low 21 young/100 females in 1985 to a high of 126 young/100 females in 1998. The mean value for young /100 females for all years of the analysis is 69. The long-term trend for young/100 females is decreasing slightly.

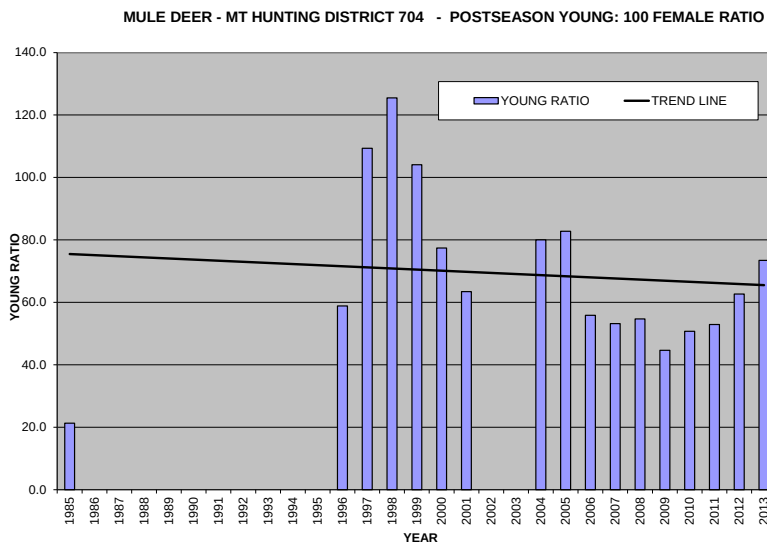


Fig. 17. Mule deer - Montana hunting district 704 – young/100 female ratios

Harvest Total male harvest for this hunting district has ranged from a low 1,310 bucks in 1981 to a high of 3,298 bucks in 1992. The average for buck harvest for all years of the analysis is 2,238 animals. The long-term trend for buck harvest is decreasing. Buck harvest in this hunting district has not met or exceeded the long term average for harvest since 2004.

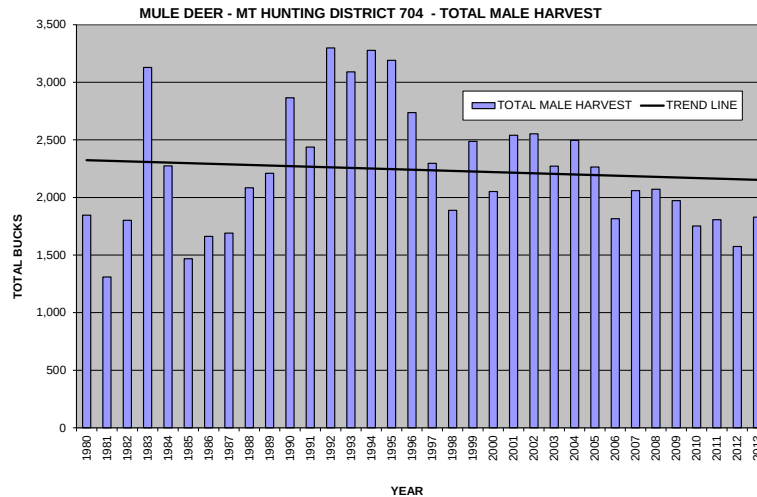


Fig. 18. Mule deer - Montana hunting district 704 – male harvest

Total harvest for the hunting district has fluctuated from a low of 1,389 animals in 1981 to a high of 6,495 animals in 1984. The mean value for harvest for all years of the analysis is 3,430 animals. The long-term trend for harvest is decreasing. There were 2 peaks of total harvest, one in the mid-1980s and another in the mid-1990s. Harvest in the 2000s and 2010s hasn't come within a thousand animals of equaling the harvest that occurred in this unit in the 1980s and 1990s.

Antlerless harvest (does and fawns) has occurred in the hunting district in all years of the analysis. Antlerless harvest has accounted for 10% of the total harvest in all years except 1980 and 1981 and accounted for as much as 65% of the total harvest in 1984.

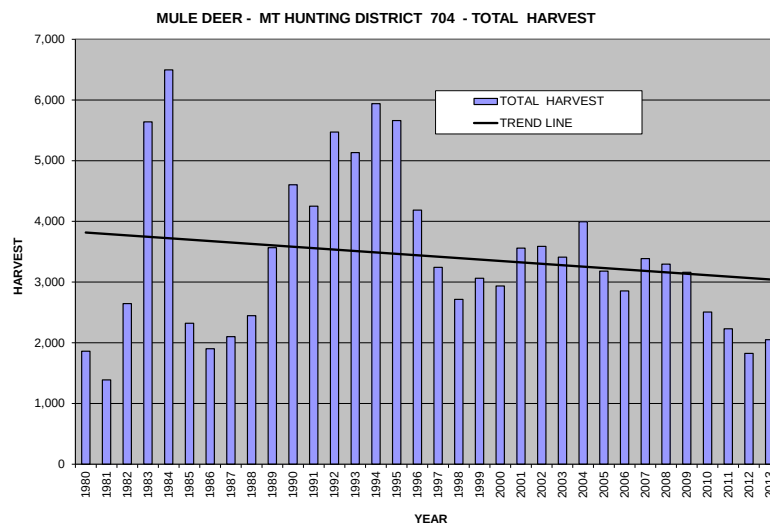


Fig. 19. Mule deer - Montana hunting district 704 – total harvest

Hunter Numbers and Success Rates Total hunting pressure (all seasons and methods of take) has ranged from a low 1,955 hunters in 1981 to a high of 7,189 hunters in 1995. The mean value for hunting pressure for all years of data is 4,841 hunters. The long-term trend for hunting pressure is increasing slightly.

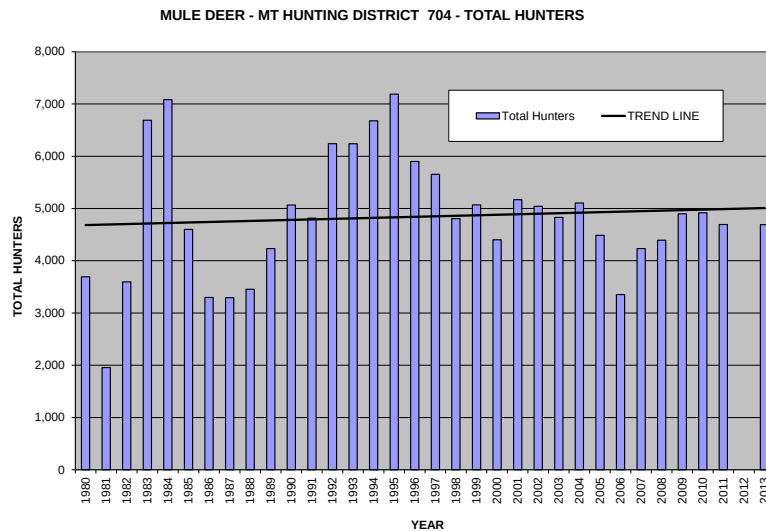


Fig. 20. Mule deer - Montana hunting district 704 – total hunters

Hunter success rates for all methods of take have varied from a high of 92% success in 1984 to a low of 44% success in 2013. The mean value for hunter success rates for all years of data is 71% success. The long-term trend for hunter success is declining. There have been 3 peaks of hunter success in this hunting district in the past in 1984 (92% success), in 1990 (91% success) and in 2006 (85% success). Hunter success for 2013 is the lowest recorded for this hunting district (44%) and is substantially below the mean for hunter success in this district (71%).

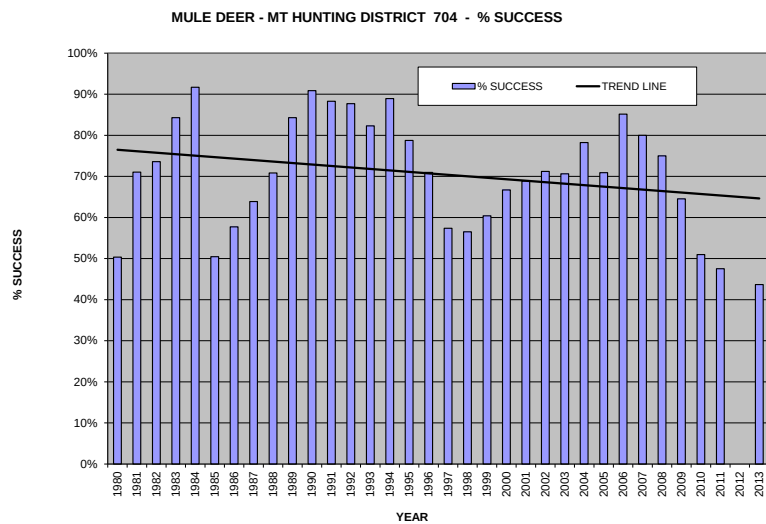


Fig. 21. Mule deer - Montana hunting district 704 – hunter success rates

Summary of Herd Vital Statistics and Management Implications Again, an evaluation of a variety of data for the mule deer herd in this hunting district indicates that it is not performing at an optimum level. According to the evaluation system that was used to evaluate previous hunting districts, the performance rating for this herd would be fair for the following reasons:

- The long-term trend for young/100 female ratios is declining, slightly. This may be an indicator that at the current population size, the available habitat isn't sufficient to provide for good fawn production and survival.

- The long-term trend for harvest is also declining. The harvest for the 2013 hunting season was 2,050 animals which is substantially below the long-term mean for harvest of 3,430 animals. This is an indication that current levels of production and survival are not sufficient enough to support higher levels of harvest.
- On a positive note, the long-term trend for population size appears to be stable.

The above information indicates, even if current habitat conditions are maintained, it is unlikely that this herd will show dramatic improvements in population size and harvest. It also indicates that if habitat conditions deteriorate due to loss of habitat due to development or adverse natural conditions (severe winters or extended periods of drought) harvest and population size will likely decrease.

MULE DEER HUNTING DISTRICT 705 (refer to appendix, tables 33 & 33A)

General Description Mule deer hunting district 705 is located in southeastern Montana and is commonly known as the Prairie Pines-Juniper Breaks hunting district. The hunting district lies in portions of Bighorn, Custer, Fallon, Powder River, Prairie and Rosebud counties. The hunting district is bounded on the north by U. S. Highway 12, on the east by the Montana/North Dakota state border, on the south by the Montana/Wyoming state border and on the west by the Broadus-Moorhead Road and the Broadus/Powderville Road. The hunting district is one of 3 hunting districts, along with hunting districts 702 and 704 that covers an area of approximately 14,378 square miles. Hunting district 705 is the largest of the 3 hunting districts. Virtually all of the hunting district is considered to be occupied mule deer habitat.

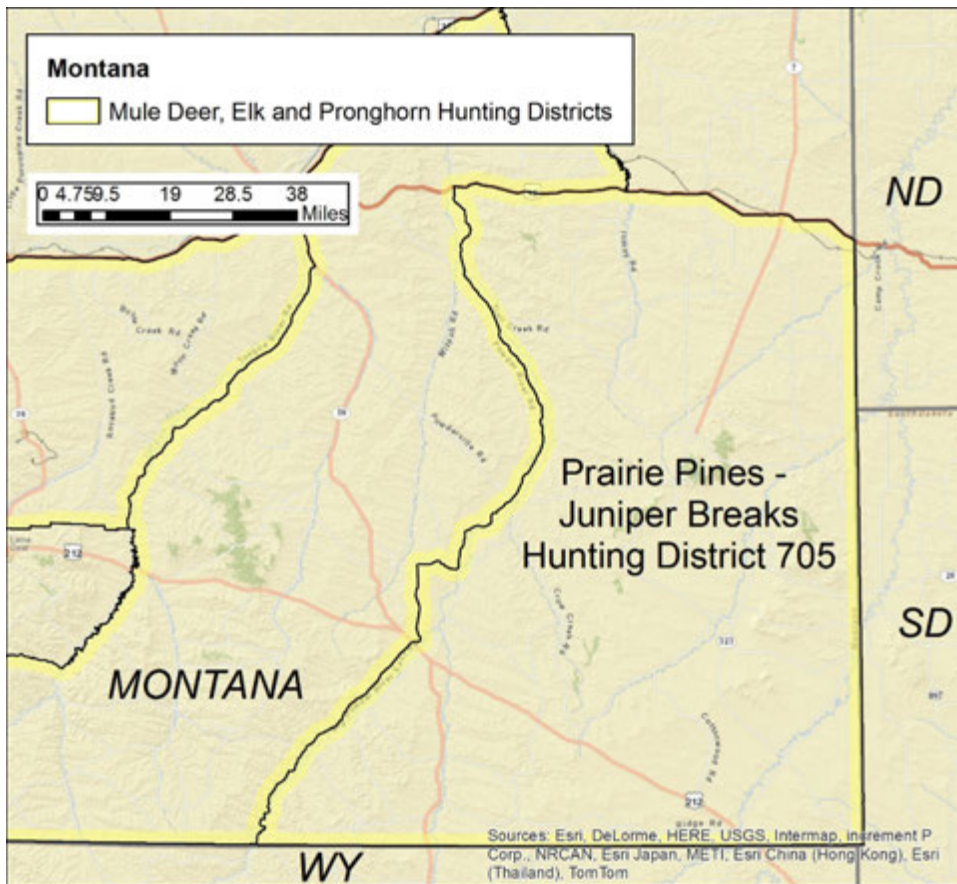


Fig. 22. Montana hunting district 705

The landscape in the hunting district is part of an area described as the northwest Great Plains eco-region. This main eco-region is further divided into 5 sub-sections designated as; river breaks, forested buttes, sagebrush steppe, Montana central grasslands and pine scoria hills. The river breaks sub-section is composed of rugged, highly dissected terrain bordering major rivers. Vegetation in this sub-section varies from western wheatgrass and buffalo grass on level bottom lands to threadleaf sedge and needle and thread grass on south facing slopes and junipers and deciduous trees on north facing slopes of drainages.

The forested buttes sub-section contains prominent, mostly forested buttes with steep sides and grassy toe slopes and headwater areas with numerous springs. Vegetation of this sub-section characteristically includes ponderosa pine and ponderosa pine-savannah as well as snowberry, Rocky Mountain juniper, and boxelder in the draws.

The sagebrush steppe subsection is a nearly level to rolling, erosion prone plain with occasional eroded buttes, badlands, scoria (burnt coal) mounds, and salt pans. Streams are typically ephemeral or intermittent and many small water ponds are present. The sparse vegetative cover is composed of wheatgrass and needlegrass but is often dominated by big sagebrush, Nuttall saltbush, and short grass prairie. Extensive areas of this sub-section have been overgrazed and have experienced resultant erosion.

The Montana central grasslands sub-section is a dissected rolling plain studded with buttes and intersected with intermittent or ephemeral streams. Vegetation in this sub-section includes gramma grass, needlegrass and wheatgrass.

Pine scoria hills is the fifth sub-section of the eco-region. This segment consists of stony, rough hills. Vegetation varies from eastern ponderosa pine forest to pine savannah with large patches of grassland (Woods et al. 2002). In this hunting district the approximate percent composition of the various subsections of habitat described above is; river breaks – 15%, forested buttes – 10%, sagebrush steppe – 25%, Montana central grassland – 40% and pine scoria hills – 10%.

Land Ownership Approximately 25% of the area is public land administered primarily by the U. S. Forest Service, Bureau of Land Management and Montana Department of Natural Resources and Conservation. The other 75% is in private ownership (MFWP 2004).

Land Use Much of the private land in the hunting district is used for livestock grazing, primarily cattle. Some farming occurs especially in the larger valleys. Drilling for coal-bed methane and surface mining for coal are examples of energy development that has occurred in the area. Urban and sub-urban development includes the communities of Broadus (pop. 468), Baker (pop. 1741) and Ekalaka (pop. 332) (2010 Census Interactive Population Search). The remainder of the human population in the hunting district is in small, un-incorporated communities, settlements or individual ranches or home sites throughout the hunting district.

Management Issues Hunting access on private lands is a significant issue that limits deer harvest in some areas of the hunting district. In addition, severe environmental conditions in the form of periodic droughts or harsh winter weather occasionally impacts fawn survival in this hunting district.

Population Size Records of deer population size for this hunting district are incomplete. The estimates for population size are from the Harding, Horse Creek and Tie Creek trend count areas that Montana Fish Wildlife and Parks (MFWP) monitors. Data from the 3 trend count areas indicate that numbers of deer on the trend areas have fluctuated from a low of 215 deer in 1997 to a high of 647 deer in 2007. The 2012 estimate for population size is 492 animals. The mean value for numbers of deer observed on the trend areas is 447 animals. The long-term trend for deer on the trend count area is increasing. No long term objective for density or population size has been established for the trend count area.

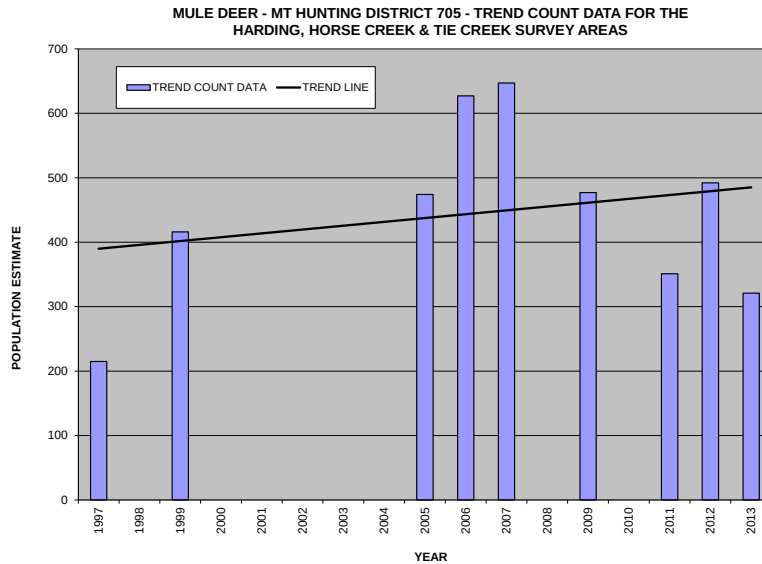


Fig. 23. Mule deer - Montana hunting district 705 – Harding, Horse Creek and Tie Creek trend count data.

Age and Sex Composition Male/100 female ratios have ranged from a high of 47 males/100 females in 2001 to a low of 16 males/100 females in 2003. The mean for all years of data is 28 males/100 females. The long-term trend for male/100 female ratios is decreasing slightly.

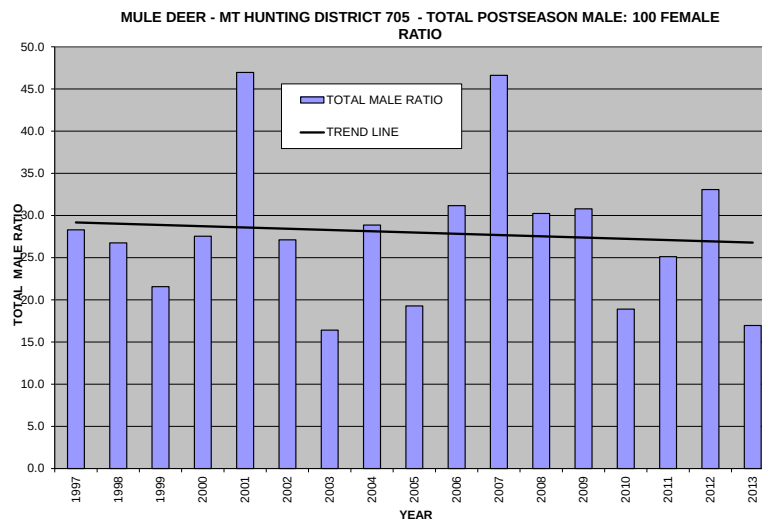


Fig. 24. Mule deer - Montana hunting district 705 – male/100 female ratios

Young/100 female ratios have ranged from a high of 84 young/100 females in 2007 to a low of 32 young/100 females in 2010. The mean value for young/100 females is 66. The long-term trend for young/100 females is decreasing.

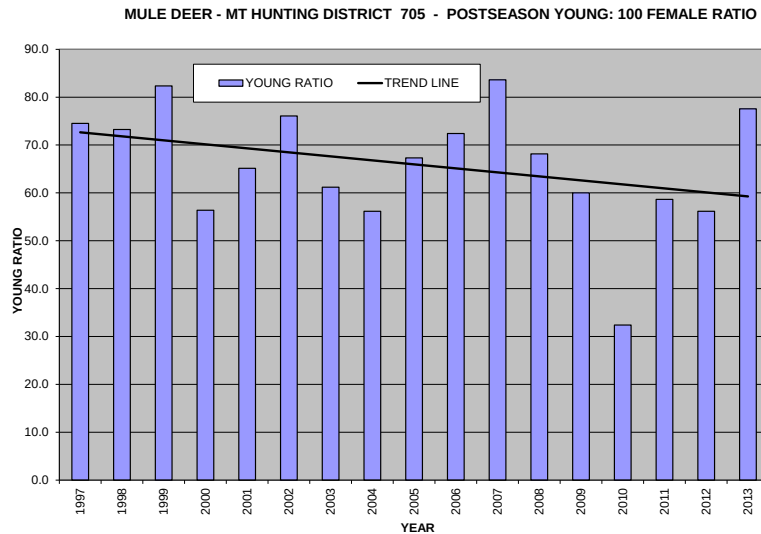


Fig. 25. Mule deer - Montana hunting district 705 – young/100 female ratios

Harvest Male harvest for this hunting district has ranged from a high of 3,290 animals in 1983 to a low of 958 animals in 1987. The average for male harvest for all years of the analysis is 1,937 animals. The long-term trend for harvest is decreasing slightly. A comparison of the average harvest of bucks by decade shows that the 2000s were the 10 year period with the highest average buck harvest for this hunting district while it was the 1980s or 1990s in other hunting districts in southeastern Montana. The last time male harvest met or exceed the average for buck harvest in the district was 2007.

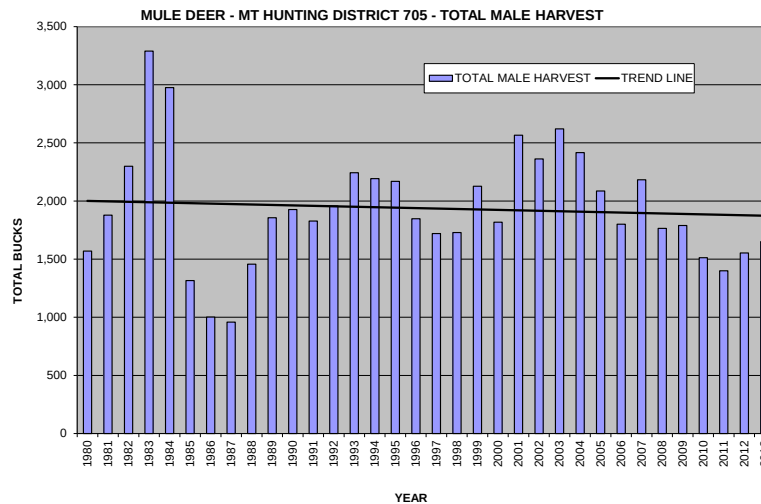


Fig. 26. Mule deer - Montana hunting district 705 – male harvest

Total harvest for this hunting district has fluctuated substantially over the years. The maximum harvest reported for the district was 10,035 animals in 1984 and the minimum harvest was 1,227 1986. The mean value for total harvest is 3,402 animals. The long-term trend for harvest is decreasing. The mean harvest of deer in the 2010s is only about half of the mean harvest of deer for previous decades.

Antlerless harvest (does and fawns) has occurred in the hunting district for all years of the analysis, but the variation is extreme, ranging from a low of 75 animals in 1980 to a high of 7,059 antlerless animals in 1984 (70% of the total harvest).

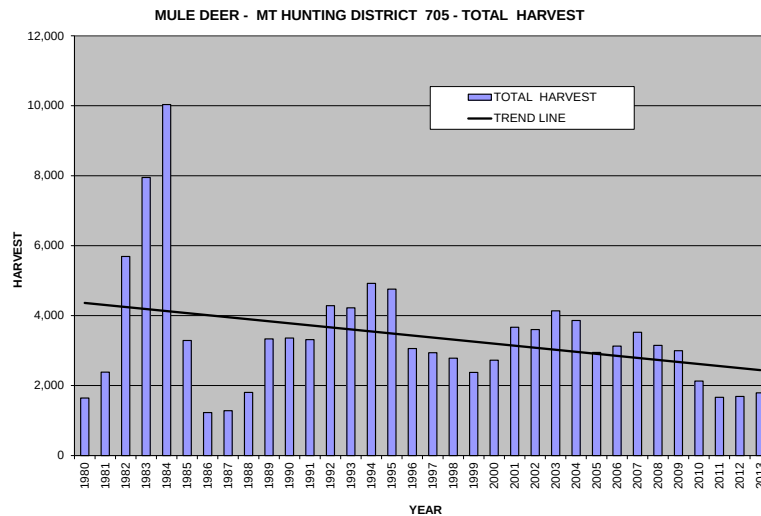


Fig. 27. Mule deer - Montana hunting district 705 – total harvest

Hunter Numbers and Success Rates Total hunting pressure for all seasons and methods of take has varied from a high of 11,306 in 1984 to a low 2,771 hunters in 1987. The mean value for hunting pressure is 5,008 hunters. The long term trend for hunter numbers is decreasing.

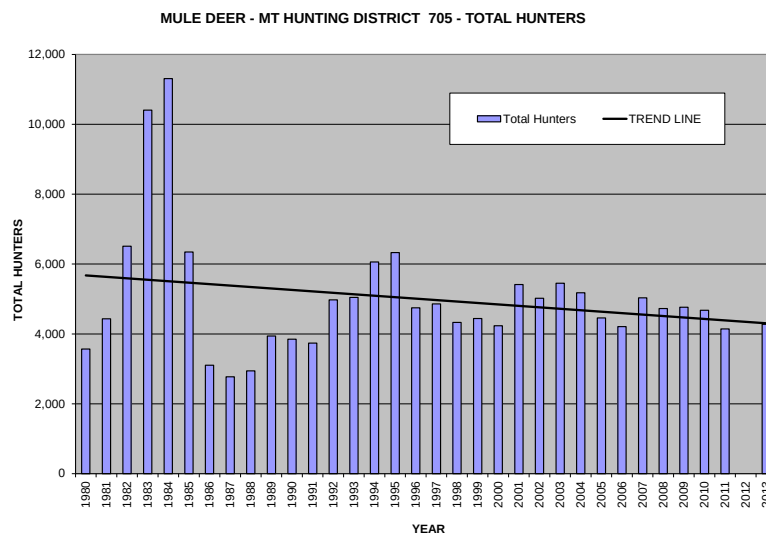


Fig. 28. Mule deer - Montana hunting district 705 – total hunters

Hunter success rates for all methods of take have varied from a high of 89% success in 1984 to a low of 40% success in 1986 and again 2011. The mean value for hunter success rates is 67%. The long-term trend for hunter success is declining.

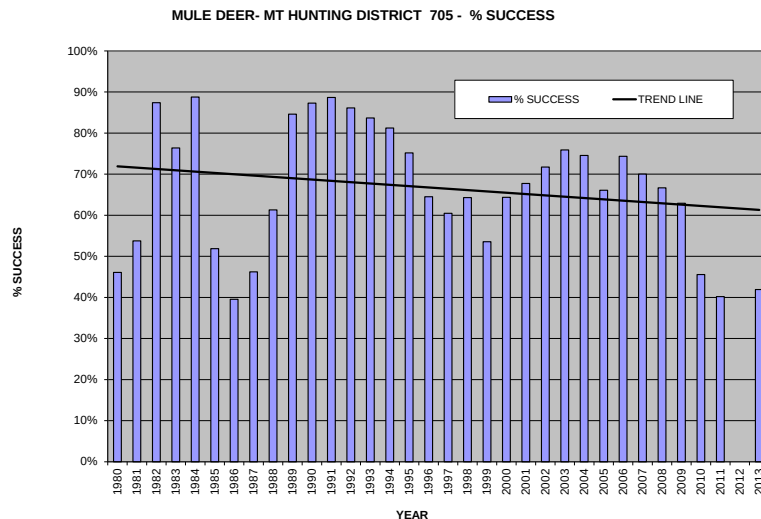


Fig. 29. Mule deer - Montana hunting district 705 – hunter success rates

Summary of Herd Vital Statistics and Management Implications An evaluation of a variety of data for the mule deer herd in this hunting district indicates that it is not performing at an optimum level. According to the evaluation process that was developed for this project, the performance rating for this herd would be fair for the following reasons:

- The long-term trend for young/100 female ratios is declining. However, the ratios observed for 2013 (78 young/100 females) is greater than the ratios recorded for the 3 previous years and the 2013 value is above the long-term mean for young/100 female ratios of 66 young/100 females.
- Another negative factor for this deer herd is a decreasing long-term trend for harvest. The total harvest of 1,792 animals in 2013 is the fifth lowest harvest recorded in the 32 year period of this data analysis and is only 53% of the long-term mean for harvest (3,402).
- The long-term trend for population size for the 3 trend areas that are monitored for this hunting district is increasing. This metric may be misleading and may not be a reliable indicator of what is happening with population size for the entire hunting district. Also, even though the long-term trend is increasing, the population estimate of 312 animals for the 3 trend count areas is the second lowest value recorded since 1997.

The upshot of all of this information is that if current habitat conditions are maintained, this deer herd will not likely show an improvement in population size and harvest in the near future. Also, if habitat conditions deteriorate for whatever reason, population size and harvest will likely decline further than current levels.

ELK HUNTING DISTRICT 702 (refer to appendix, table 28)

General Description Please refer to the general description information and Fig. 6 that is provided for deer Hunting District 702. Hunting district 702 for mule deer is identical to elk hunting district 702.

Land Ownership Please refer to the land ownership information for deer hunting district 702

Land Use Please refer to the land use information for deer hunting district 702

Management Issues Hunting access on private lands is a significant issue that limits elk harvest in some areas of the hunting district. Fee hunting or outfitting also limits hunter access in some

areas, resulting in the creation of refuge areas for elk that makes it difficult to achieve harvest objectives in some areas (MFWP 2004).

Population Size No population size information is available for elk hunting district 702.

Age and Sex Composition Only one year of age and sex composition information is available for elk hunting district 702. There are 78 males/100 females and 71 young/100 females reported for 2012 in this hunting district.

Harvest Male harvest for this hunting district has ranged from a low of 1 bull harvested in 1994 to a high of 38 bulls harvested in 2011. Average bull harvest for this hunting district is 14 animals. The long-term trend for bull harvest is increasing and a review of the amount of bull harvest by decade shows that the 2010s had the highest average bull harvest since elk hunting started in this hunting district in the early 1990s.

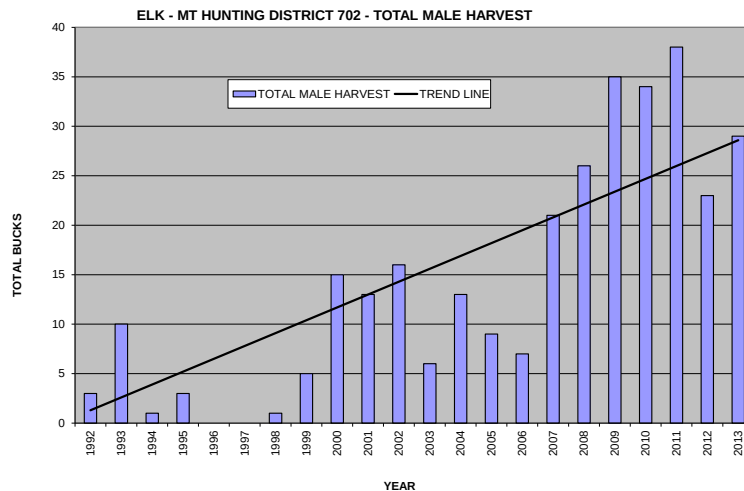


Fig. 30. Elk - Montana hunting district 702 – male harvest

Total harvest for the hunting district has ranged from a low of 0 animals in 1996 and 1997 to a high of 128 animals in 2012. The mean value for harvest for this herd unit is 36 animals. The long-term trend for harvest is increasing.

Antlerless harvest (cows and calves) has occurred in this hunting district since 1992. Antlerless harvest has accounted for 50% or more of the total harvest in 11 of 22 years that antlerless animals were harvested, and accounted for 82% of the total harvest in 2012.

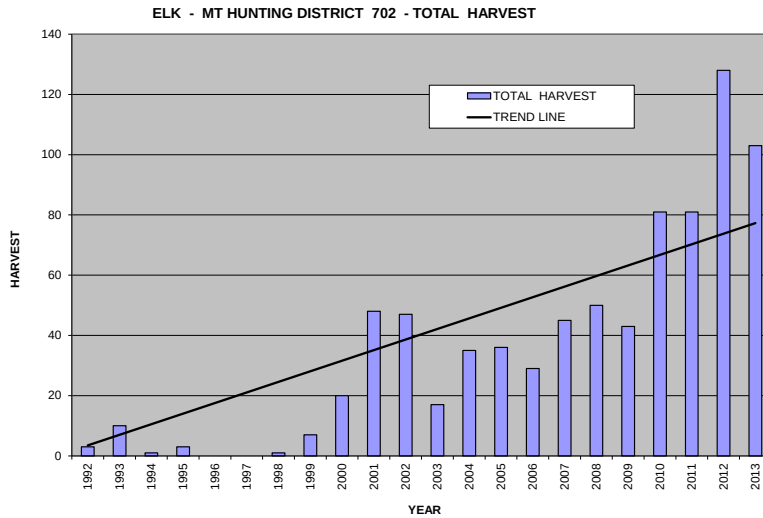


Fig. 31. Elk - Montana hunting district 702 – total harvest

Hunter Numbers and Success Rates Total hunting pressure has varied from a low of 150 hunters in 2005 to a high of 523 hunters in 2012. The mean value for hunting pressure is 277 hunters. The long-term trend for hunting pressure is increasing.

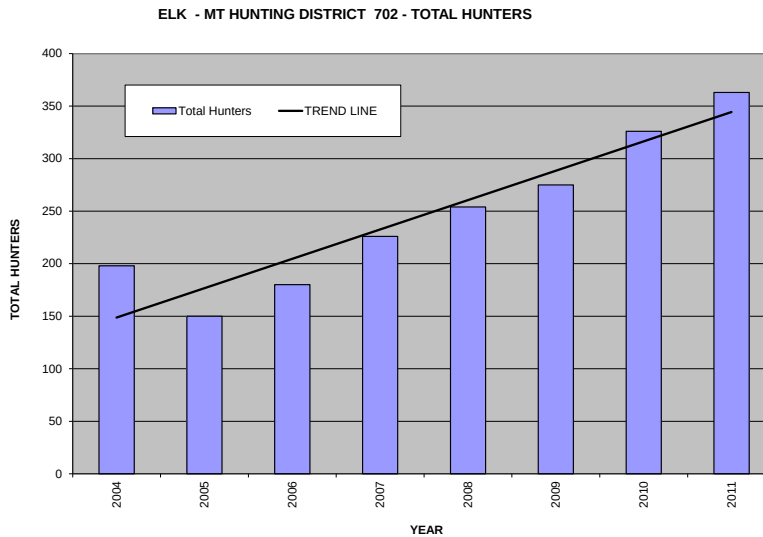


Fig. 32. Elk - Montana hunting district 702 – total hunters

Hunter success rates in this hunting district have ranged from a low of 16.1% in 2006 to a high of 24.5% in 2012. The mean value for hunter success rates is 21%. The long-term trend for hunter success rates is increasing.

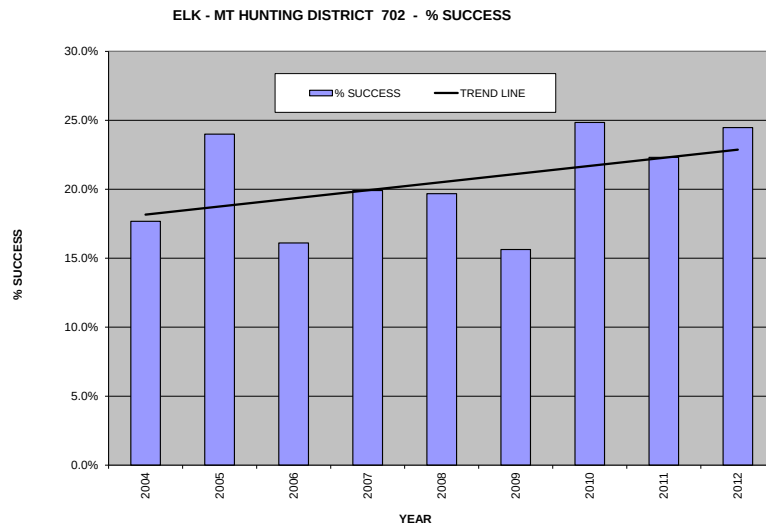


Fig. 33. Elk - Montana hunting district 702 – hunter success rates

Summary of Herd Vital Statistics and Management Implications It isn't possible to do the customary summary of herd vital statistics for this hunting district as the data set is incomplete. Estimates for population size and herd composition aren't available. It is understood that the elk population that occupies this hunting district has only recently grown to a size that would justify spending time and money for monitoring and evaluation.

ELK HUNT AREA 704 (refer to appendix, table 29)

General Description Please refer to the general description information provided for deer hunting district 704 (page 48) as the deer and elk hunting district boundaries are identical.

Land Ownership Please refer to the land ownership information provided for deer hunting district 704.

Land Use Please refer to the land use information provided for deer hunting district 704.

Management Issues Hunting access on private lands is a significant issue that limits elk harvest in some areas of the hunting district. Fee hunting or outfitting also limits hunter access in some areas, resulting in the creation of refuge areas for elk that makes it difficult to achieve harvest objectives in some areas (MFWP 2004).

Population Size No information is available concerning the size of the elk population in hunting district 704.

Age and Sex Composition

Males/100 females ratios for this hunting district range from a high of 34 males/100 females in 2010 to a low of 17 males/100 females in 2012. The mean value for male/100 female ratios is 24:100. The long-term trend for male/100 female ratios is decreasing slightly.

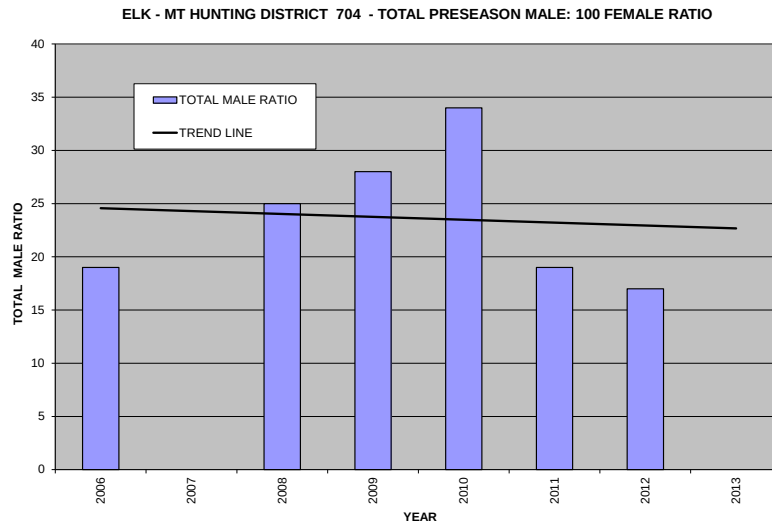


Fig. 34. Elk - Montana hunting district 704 – male/100 female ratios

Young/100 female ratios range from a high of 53 young/f100 females in 2008 to a low of 28 young/100 females in 2009. The mean value for young/100 female is 43:100. The long-term trend for young/100 females is decreasing for this unit.

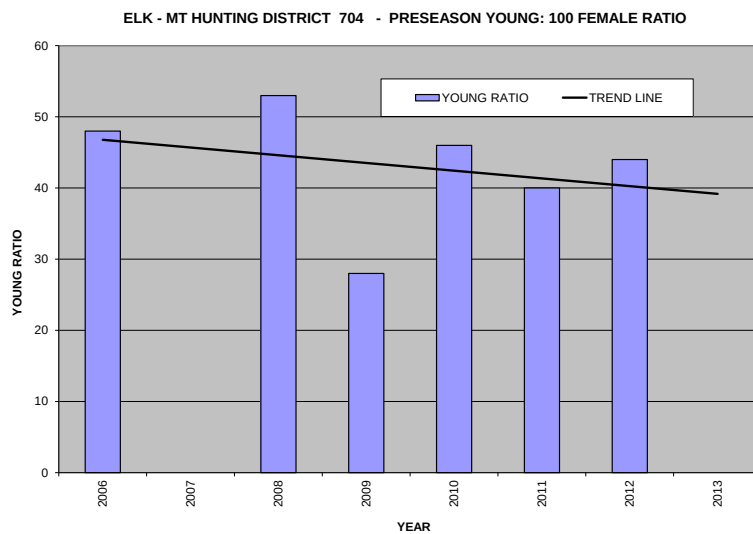


Fig. 35. Elk - Montana hunting district 704 – young/100 female ratios

Harvest Male harvest for this herd unit has ranged from a low of 4 bulls harvested in 1992 to a high of 92 bulls harvested in 2013. Average bull harvest for all years of the analysis is 33 animals. The long-term trend for male harvest is increasing. A review of bull harvest by decade shows the 2010s with the highest average harvest by decade.

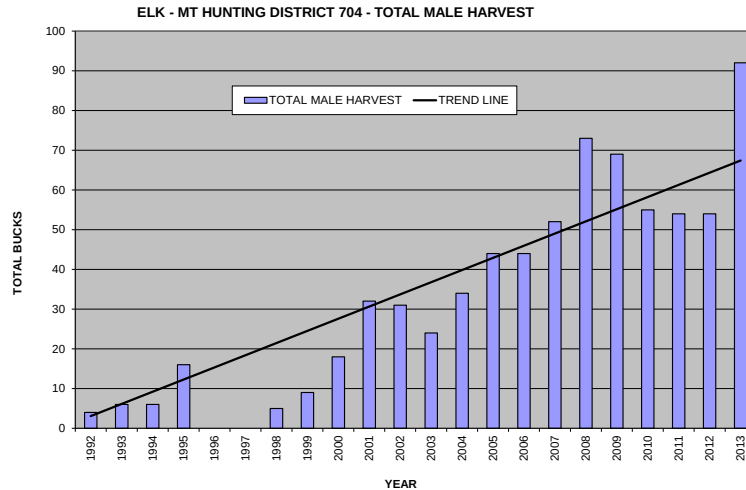


Fig. 36. Elk - Montana hunting district 704 – male harvest

Total harvest for elk hunting district 704 has ranged from a low of 0 animals in 1996 and 1997 to a high of 214 animals in 2013. The mean value for harvest for this unit is 42 animals. The long-term trend for harvest for the hunting district is increasing.

Antlerless harvest (cows and calves) for the hunting district has occurred since 1992. Antlerless harvest has averaged 42 animals a year and has accounted for more than 15% of the total harvest in all years and as much as 69% of total harvest in 2011.

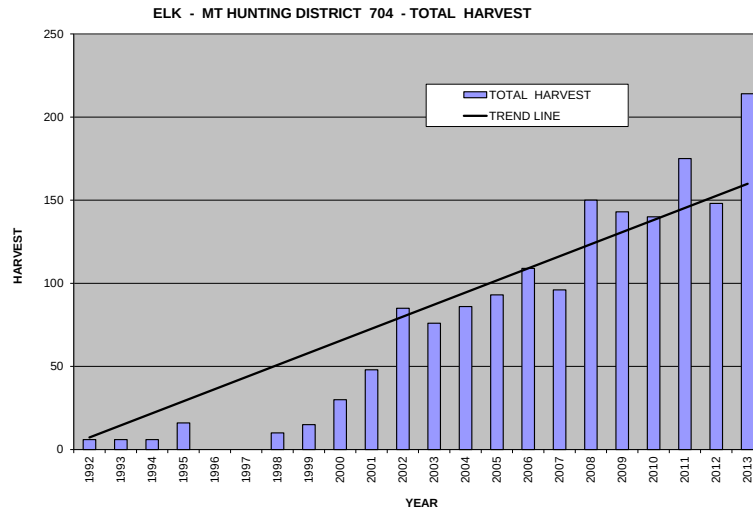


Fig. 37. Elk - Montana hunting district 704 – total harvest

Hunter Numbers and Success Rates Total hunting pressure for this unit has ranged from a low of 458 hunters in 2006 to a high of 840 hunters in 2009. The mean for hunting pressure is 656 hunters. The long-term trend for hunting pressure is increasing.

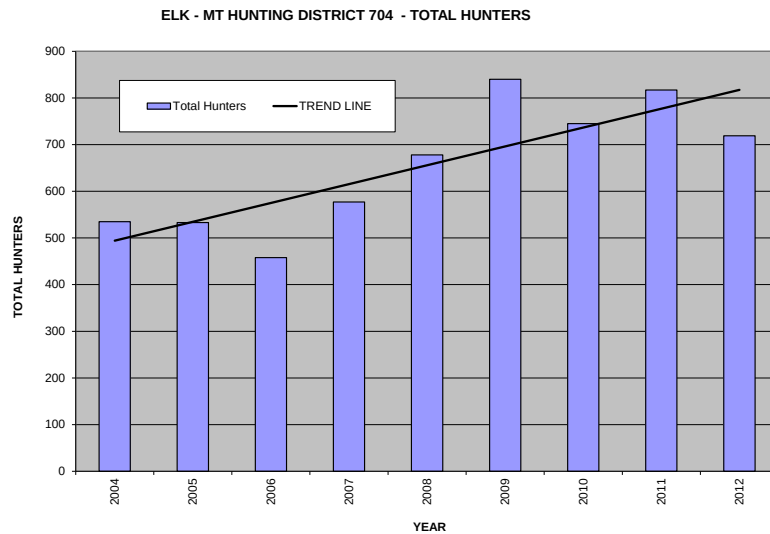


Fig. 38. Elk - Montana hunting district 704 – total hunters

Hunter success rates have ranged from a low of 16.1% in 2004 to a high of 23.8% in 2006. The mean value for hunter success is 19%. The long-term trend for hunter success in this unit is increasing.

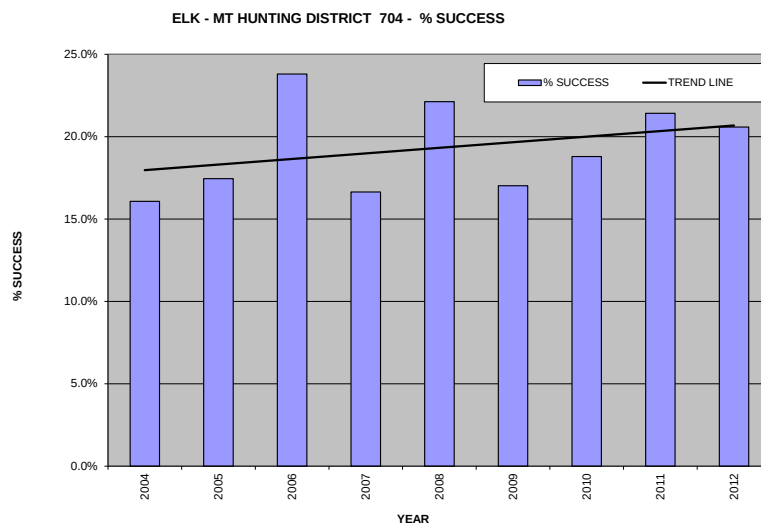


Fig. 39. Elk - Montana hunting district 704 – hunter success rates

Summary of Herd Vital Statistics and Management Implications It isn't possible to do the customary summary of herd vital statistics for this hunting district as the data set is incomplete. Only one estimate for population size is available (1,070 in 2012). It is understood that the elk population that occupies this hunting district has only recently grown to a size that would justify spending time and money for monitoring and evaluation.

ELK HUNT AREA 705 (refer to appendix, table 30)

General Description

Please refer to the information in the general description for deer hunting district 705 (page 54) as the boundaries for the hunting districts are identical.

Land Ownership Please refer to the information concerning land ownership for deer hunting district 705 as the information is identical.

Land Use Please refer to land use information included in deer hunting district 705.

Management Issues

Hunting access on private lands is a significant issue that limits elk harvest in some areas of the hunting district. Fee hunting or outfitting also limits hunter access in some areas, resulting in the creation of refuge areas for elk that makes it difficult to achieve harvest objectives in some areas (MFWP 2004)

Population Size The information on elk population size for this hunting district is incomplete. A value for population size is only reported for 2013 in which the elk population is estimated at 432 animals.

Age and Sex Composition Again, age and sex composition information for the elk herd in this hunting district is very limited. The only information that is available is for 2011 and male/100 females ratios are reported to be 41:100 and young/100 female ratios are reported as 53:100.

Harvest Male harvest for this hunting district has ranged from a low of 0 bulls harvested in 2001 to a high of 35 bulls harvested in 2013. The average bull harvest for all years of the analysis is 17 animals. The long-term trend for bull harvest is increasing. A review of harvest by decade shows the 2010s with the highest average harvest of 29 bulls/year.

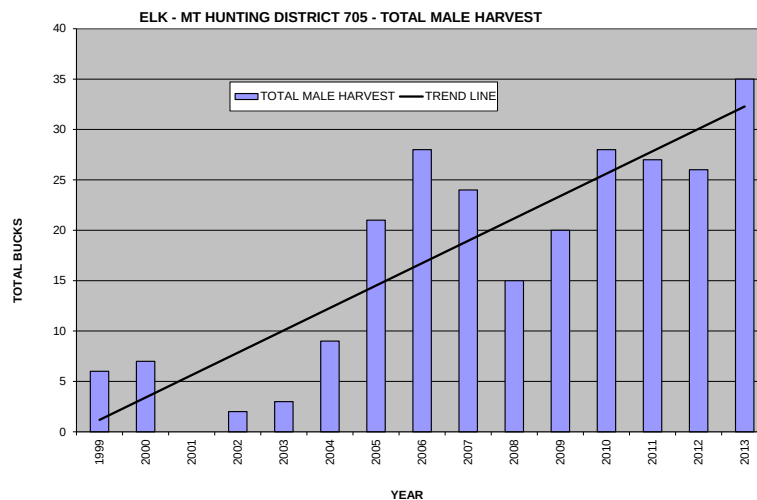


Fig. 40. Elk - Montana hunting district 705 – male harvest

Total harvest for this elk hunting district has ranged from a low of 0 animals in 2001 to a high of 62 animals in 2011. The mean value for elk harvest is 35 animals for this unit. The long-term trend for harvest is increasing.

Antlerless harvest has occurred in the hunting district since 2002. It accounts for at least 40% of the total harvest in all years and as much as 84% of the total harvest in 2002.

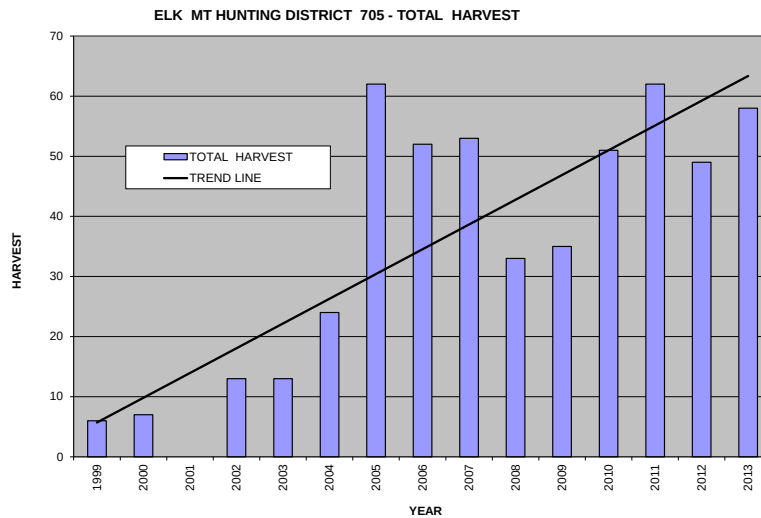


Fig. 41. Elk - Montana hunting district 705 – total harvest

Hunter Numbers and Success Rates Total hunting pressure for the hunting district has ranged from a low of 147 hunters in 2004 to a high of 277 hunters in 2012. The mean value for hunting pressure for the unit is 212 hunters. The long-term trend for hunting pressure is increasing.

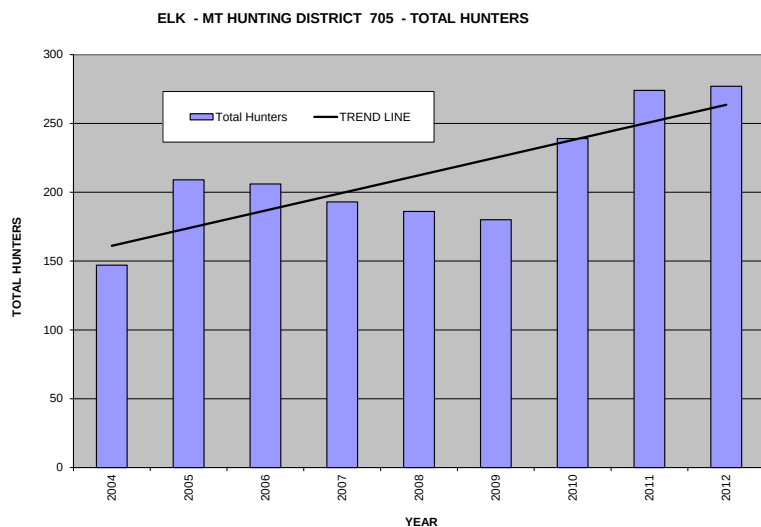


Fig. 42. Elk - Montana hunting district 705 – total hunters

Hunter success rates for elk hunting district 705 have ranged from a low of 16.3% success in 2004 to a high of 29.7% success in 2005. The mean value for hunter success in the district is 22%. The long-term trend for hunter success is decreasing.

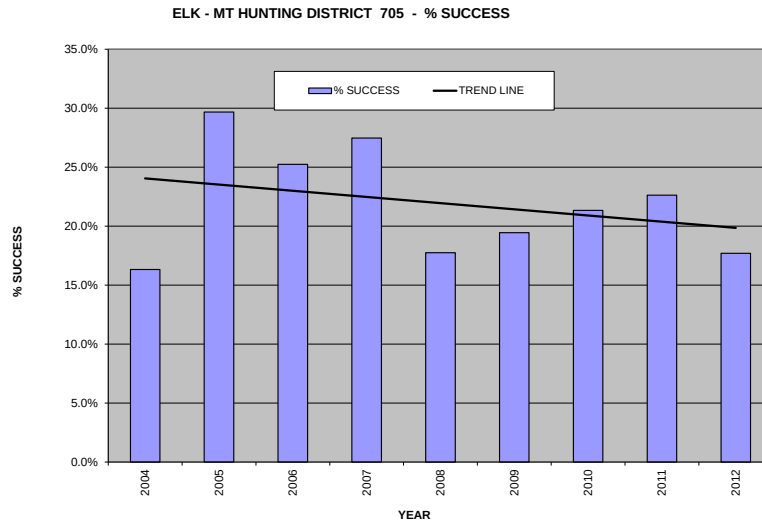


Fig. 43. Elk - Montana hunting district 705 – hunter success rates

Summary of Herd Vital Statistics and Management Implications It isn't possible to do the customary summary of herd vital statistics for this hunting district as the data set is incomplete. Also, estimates for population size and herd composition aren't available. It is understood that the elk population that occupies this hunting district has only recently grown to a size that would justify spending time and money for monitoring and evaluation.

PRONGHORN HUNTING DISTRICT 702 (refer to appendix, table 25)

General Description Please refer to deer hunting district 702 for a general description of this hunting district as the two are identical districts (page 43).

Land Ownership Please refer to deer hunting district 702 for a discussion on land ownership as the two units are identical.

Land Use Please refer to deer hunting district 702 for a discussion on land use in this hunting district.

Management Issues Hunting access on private lands is a significant issue that limits pronghorn harvest in some areas of the hunting district. In addition, severe environmental conditions in the form of periodic droughts or harsh winter weather occasionally impacts fawn survival in this hunting district.

Population Size The pronghorn population in Hunting District 702 has fluctuated substantially from a high of 4,654 animals in 2007 to a low of 1,062 animals in 2011. The mean value for population size for the district is 2,932 animals. The long-term trend for population size is decreasing. The most recent estimate for population size is 2,314 animals in 2013.

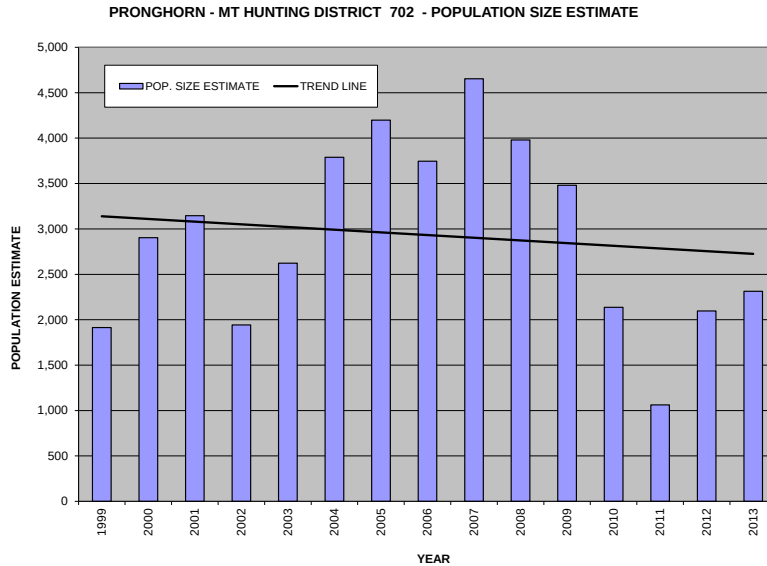


Fig. 44. Pronghorn - Montana hunting district 702 – population size estimate

Age and Sex Composition Age and sex composition information is not available for the pronghorn population in this hunting district.

Harvest Total male harvest for this hunting district has ranged from a low of 13 bucks in 1984 to a high of 446 bucks in 1995. The average male harvest for all years of the analysis is 244 bucks. The long-term trend for male harvest is stable to slightly increasing. A review of male harvest by decade shows the 1990s with the highest average harvest of 310 animals per year for the decade.

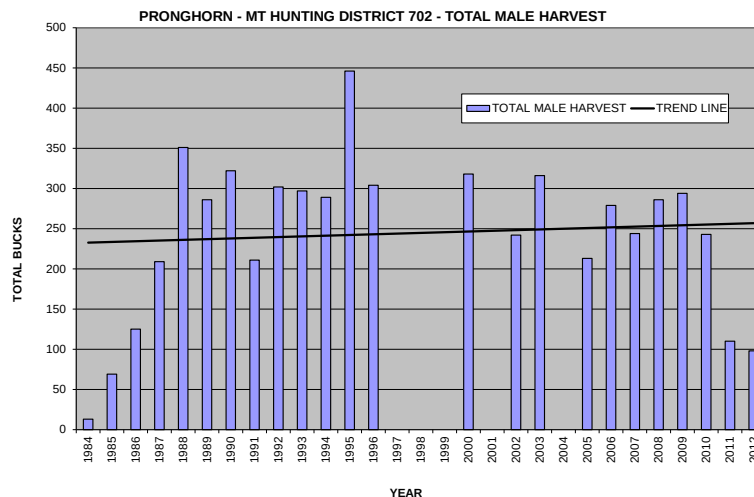


Fig. 45. Pronghorn - Montana hunting district 702 – male harvest

Total harvest of pronghorn for this hunting district has varied from a low 78 animals harvested in 1984 to a high of 684 animals harvested in 1995. The mean value for total pronghorn harvest for the district is 403 animals. The long-term trend for harvest is stable or increasing slightly. Pronghorn harvest has steadily declined in this district since 2007. The 2012 harvest of 110 animals is only 20% of the harvest that occurred in 2007 and is well below the average harvest of 403 animals per year.

Harvest of females and young has occurred in all years of the analysis. Does and fawns accounted for 83% of the total harvest in 1984 and at least 20% of the total harvest in all other years except 2012.

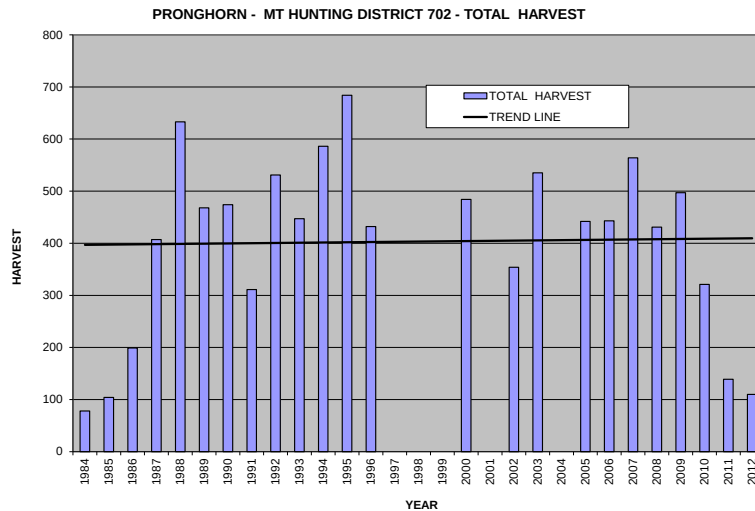


Fig. 46. Pronghorn - Montana hunting district 702 – total harvest

Hunter Numbers and Success Rates Total hunting pressure in the hunting district has varied from a low of 86 hunters in 1984 to a high of 797 hunters in 1994. The mean value for hunting pressure for the hunting district is 518 hunters per year. The long-term trend for hunting pressure is stable. However, as with harvest, numbers of hunters have declined substantially since 2007. The number of hunters in 2012 is only 28% of the hunters that hunted the district in 2007, the year of the most recent high in harvest and hunting pressure in the hunting district.

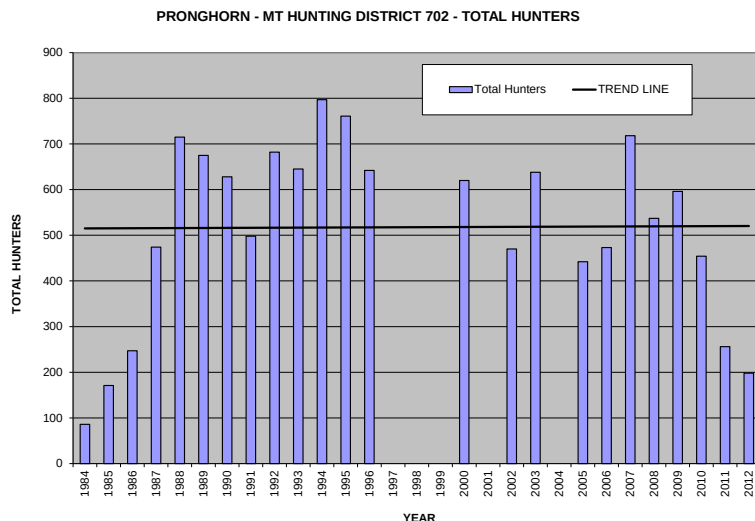


Fig. 47. Pronghorn – Montana hunting district 702 – total hunters

Although the long-term trend for hunter success rates is stable, hunter success has declined substantially in the last 7 to 8 years. Hunter success rates were at a high of 100% in 2005 but declined to a low of 54.3% in 2011. The mean value for hunter success rates in the district is 76.9% success.

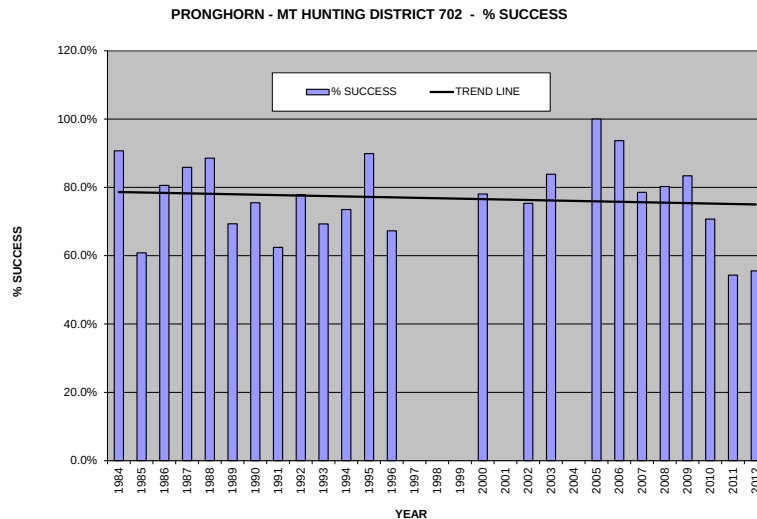


Fig. 48. Pronghorn – Montana hunting district 702 – hunter success rates

Summary of Herd Vital Statistics and Management Implications It isn't possible to do the customary summary of herd vital statistics for this hunting district as the data set is incomplete. Estimates for herd composition aren't available

PRONGHORN HUNTING DISTRICT 704 (refer to appendix, table 26)

General Description Please refer to Deer Hunting District 704 for a general description of this hunting district as the two districts are identical (page 48).

Land Ownership Again, please refer to the section on land ownership for Deer Hunting District 704 as the two districts are identical.

Land Use Please refer to deer hunting district 704 for a discussion of land use of the area.

Management Issues Hunting access on private lands is a significant issue that limits pronghorn harvest in some areas of the hunting district. In addition, severe environmental conditions in the form of periodic droughts or harsh winter weather occasionally impacts fawn survival in this hunting district

Population Size The estimates of the size of the pronghorn population in this hunting district have ranged from a low of 1,638 animals in 2011 to a high of 10,386 animals in 2013, according to Montana Fish Wildlife and Parks information. The mean value for population size for the hunting district is 5,511 animals. The long-term trend for population size is increasing.

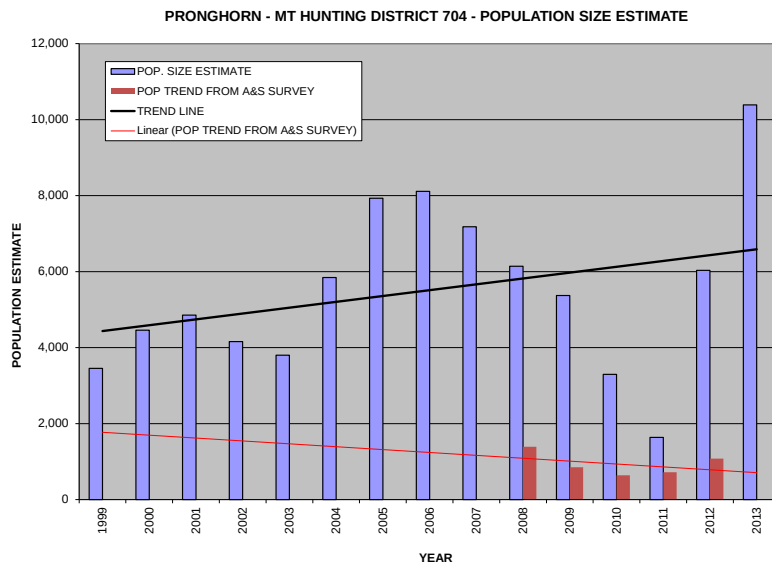


Fig. 49. Pronghorn – Montana hunting district 704 – population size estimates

Age and Sex Composition Male/100 female ratios have varied from a high of 57 males/100 females in 2008 to a low of 29 males/100 females in 2012. The mean value for male/100 female ratios is 43:100. The long-term trend for male/100 female ratios is declining.

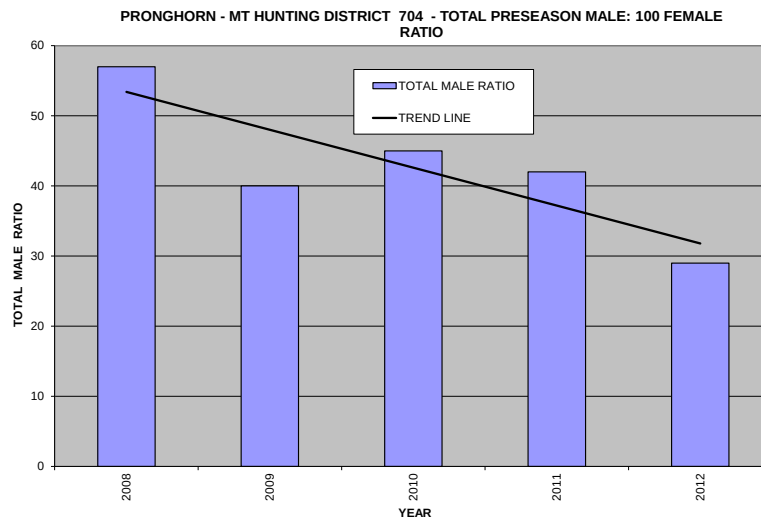


Fig. 50. Pronghorn – Montana hunting district 704 – pre-season male/100 female ratios

Young/100 female ratios have varied from a high of 38 young/100 females in 2008 to a low of 19 young/100 females in 2010. The mean value for young/100 females for the hunting district is 29:100. The long-term trend for young/100 female ratios is declining.

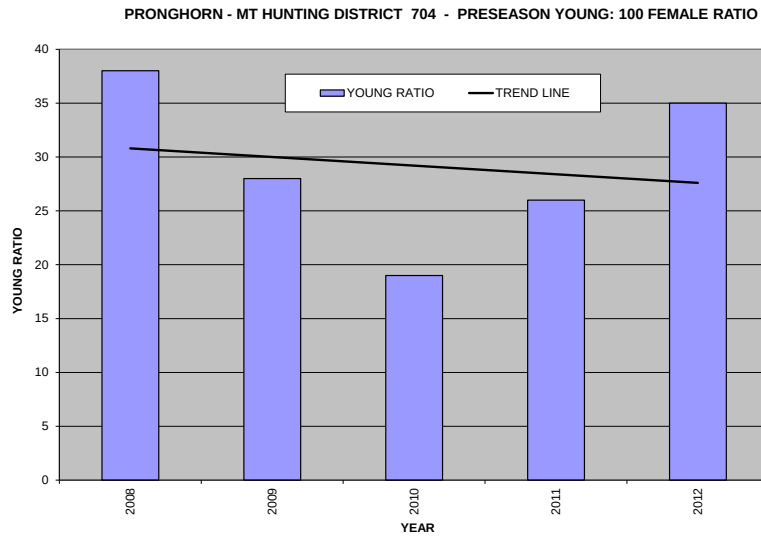


Fig. 51. Pronghorn – Montana hunting district 704 – pre-season young/100 female ratios

Harvest Total male harvest for this hunting district has varied from a high of 1,060 bucks in 1993 to a low of 190 bucks in 2012. The mean value for buck harvest for all years of the analysis is 623 animals. The long-term trend for buck harvest is decreasing. A review of buck harvest by decade shows that buck harvest has been decreasing since the 1980s when average buck harvest for the decade was 866 animals. Average buck harvest for the 2010s is 300 animals per year.

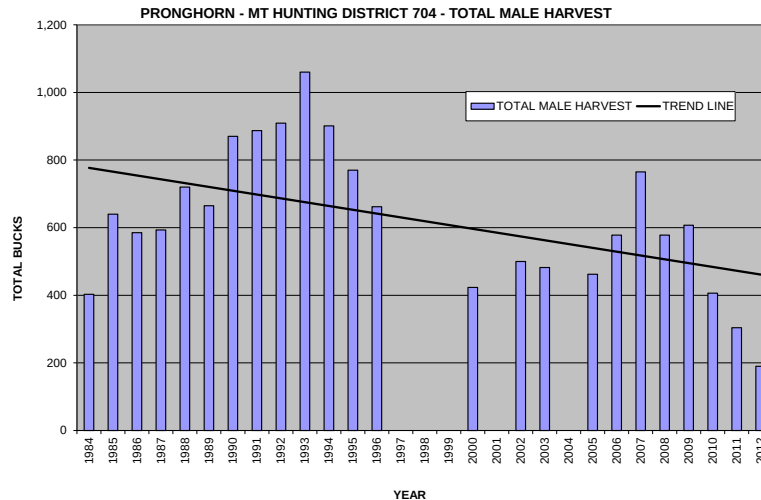


Fig. 52. Pronghorn – Montana hunting district 704 – male harvest

Total harvest of pronghorn in the hunting district has varied from a high of 1,800 animals in 1994 to a low of 222 animals in 2012, an 88% decline in harvest. The mean value for harvest for all the years of the analysis is 1,066 animals. The long-term trend for harvest is decreasing.

Does and fawn harvest in the hunting district has occurred for all years of the analysis. This harvest has ranged from a high of 899 does and fawns harvest in 1994 to a low of 32 animals harvested in 2012. The percent of total harvest accounted for by does and fawns has ranged from a high of 50% in 1994 to a low of 14% in 2012.

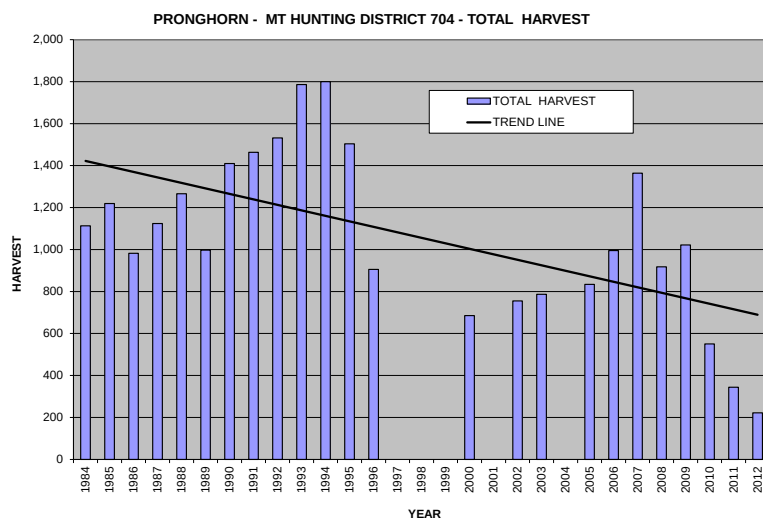


Fig. 53. Pronghorn – Montana hunting district 704 – total harvest

Hunter Numbers and Success Rates Total hunting pressure for the hunting district has ranged from a high of 2,171 hunters in 1994 to a low of 328 hunters in 2012. The mean value for numbers of hunters is 1,234. The long-term trend for hunters is declining. Hunter numbers in 2012 are only 15% of what they were in 1994.

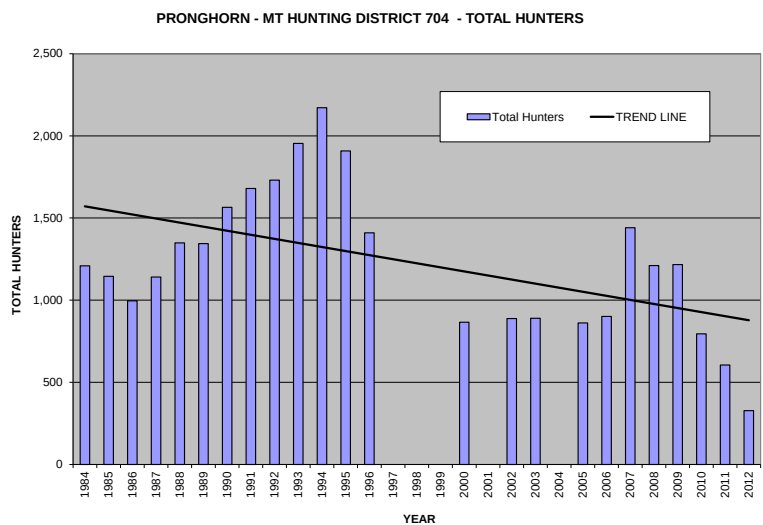


Fig. 54. Pronghorn – Montana hunting district 704 – total hunters

Hunter success rates have declined as well. Success rates for hunting district have ranged from a high of 110.4% in 2006 to a low of 56.9% in 2011. The mean value for hunter success rates is 85.6%. The long-term trend for hunter success is declining.

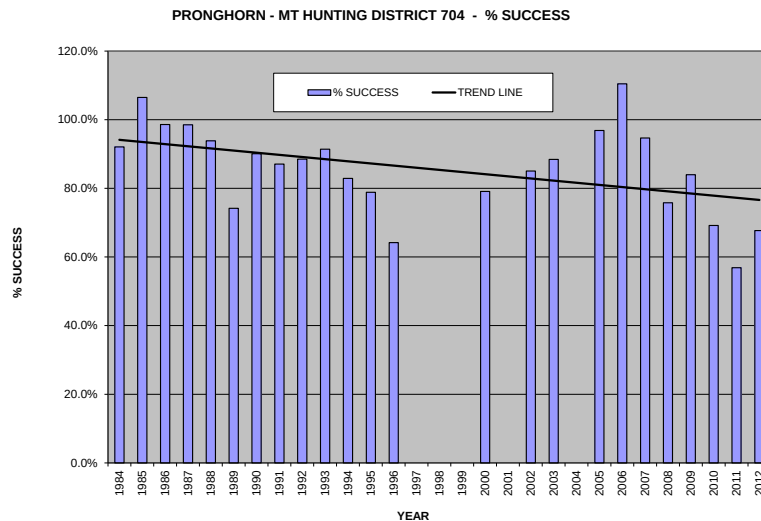


Fig. 55. Pronghorn – Montana hunting district 704 – hunter success rates

Summary of Herd Vital Statistics and Management Implications An evaluation of a variety of data for pronghorn in this hunting district indicates that it isn't performing at an optimum level. In addition, due to some conflicting data, it isn't totally clear what is happening with some of the population parameters. Despite the ambiguity of the data the rating for this herd district should be poor.

- The data for the long-term trend for population size is ambiguous. The general information indicates the long-term trend for population size is increasing. Conversely, the data set for a shorter period of time from surveys of trend count areas indicates the long-term trend is decreasing.
- The long-term trend for young/100 female ratios is decreasing despite the fact that the ratio for young/100 females has increased from 19:100 in 2010 to 35:100 in 2012. Even with the increase over the last 2 years, the current young/100 female ratio is considered insufficient for maintaining a population much less increasing the population.
- The long-term trend for harvest is decreasing. The total harvest of 222 animals reported for 2012 is the lowest value reported for 24 years of data for this hunting district. The reported harvest is only 12% of the maximum harvest reported in 1994 (1,800 animals) and is only 21% of the mean value for harvest (1,066) for the hunting district.

The outcome of all this information indicates that even if current habitat conditions are maintained, the pronghorn population is not likely to recover substantially in the near future. If habitat conditions deteriorate further, the outlook for this pronghorn population can only get worse.

PRONGHORN HUNTING DISTRICT 705 (refer to appendix, tables 27 & 27A)

General Description Please refer to Mule Deer Hunting District 705 for a general description of pronghorn hunting district 705 as their boundaries are identical (page 54).

Land Ownership Please refer to Mule Deer Hunting District 705 for a discussion about land ownership as the 2 districts are identical.

Land Use Please refer to mule deer hunting district 705 for a discussion of land use issues.

Management Issues Hunting access on private lands is a significant issue that limits pronghorn harvest in some areas of the hunting district. In addition, severe environmental conditions in the form of periodic droughts or harsh winter weather occasionally impacts fawn survival in this hunting district (Waltee 2013).

Population Size The pronghorn population size for this hunting district has fluctuated from a high of low 6,447 in 2000 to a high of 23,347 animals in 2007. The mean value for population size for all years of data is 12,947 animals. The long-term trend for population size is increasing. The 2013 estimate for population size is 13,188 animals based on projections from trend count data.

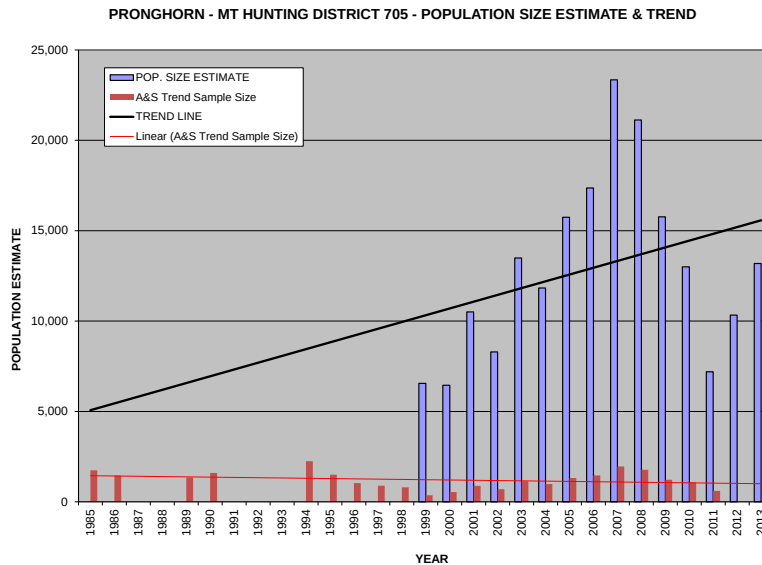


Fig. 56. Pronghorn – Montana hunting district 705 – population size estimates

Age and Sex Composition Male/100 female ratios for the hunting district have varied from a low of 19 males/100 females in 1980 to a high of 101 males/100 females in 2000. The mean value for males/100 females for all years of data for this hunting district is 61:100. The long-term trend for male/100 female ratios is increasing.

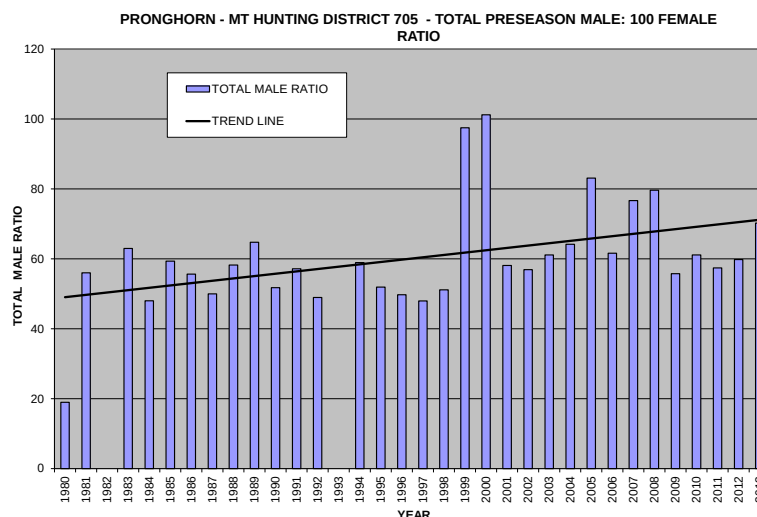


Fig. 57. Pronghorn – Montana hunting district 705 – pre-season male/100 female ratios

Young/100 female ratios have varied from a low of 45 young/100 females in 1980 to a high of 120.8 young/100 females in 2000. The mean value for young/100 females for this district is 93:100. The long-term trend for young/100 female ratios is decreasing slightly.

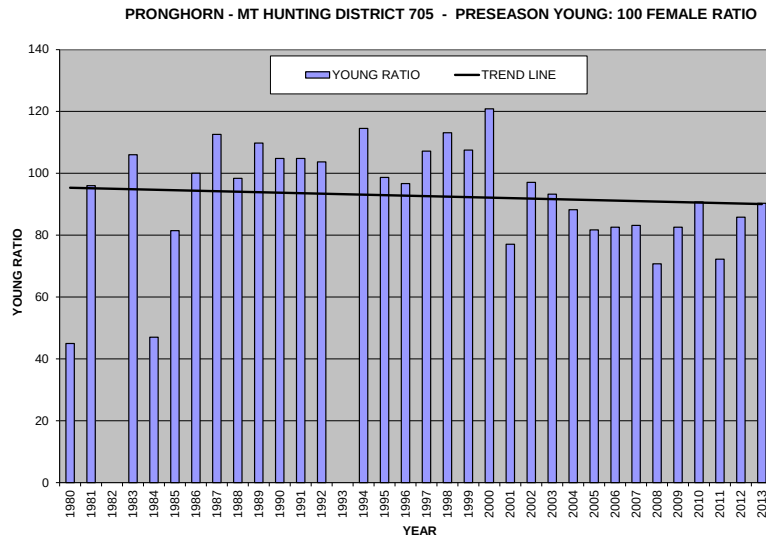


Fig. 58. Pronghorn – Montana hunting district 705 – pre-season male/100 female ratios

Harvest Male harvest has ranged from a high of 1,698 animals in 1992 to a low of 315 animals in 2012. The average for male harvest for all years of the analysis is 1,081 bucks. The long-term trend for buck harvest is declining. A review of male harvest by decade shows the 1990s with the highest average buck harvest of 1,443 animals per year. The average harvest per year for the 2010s is 514 animals which is only 36% of the annual harvest reported for the 1990s.

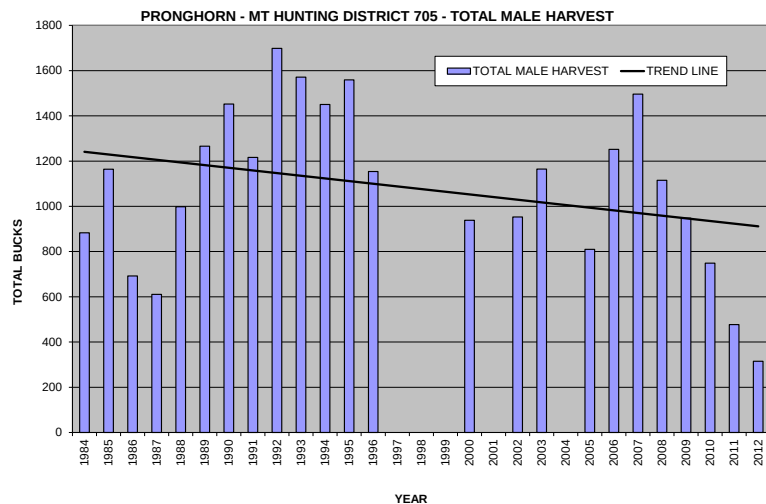


Fig. 59. Pronghorn – Montana hunting district 705 – male harvest

Total harvest of pronghorn for this hunting district has varied from a high of 3,879 in 1994 to a low of 361 in 2012. The mean value for pronghorn harvest for this hunting district is 2,055 pronghorn. The long-term trend for harvest is declining. The harvest of 361 animals in 2012 is only 9.3% of the maximum harvest for the hunting district and only 17.5% of the mean harvest for the hunting district.

Harvest of does and fawns has occurred in the hunting district for all years of the analysis. Doe and fawn harvest has ranged from a high of 2,777 animals in 1984 to a low of 46 animals in 2012.

Does and fawns have accounted for as much as 75% of the total harvest in 1984 but never less than 30% of the total harvest in all other years of the analysis.

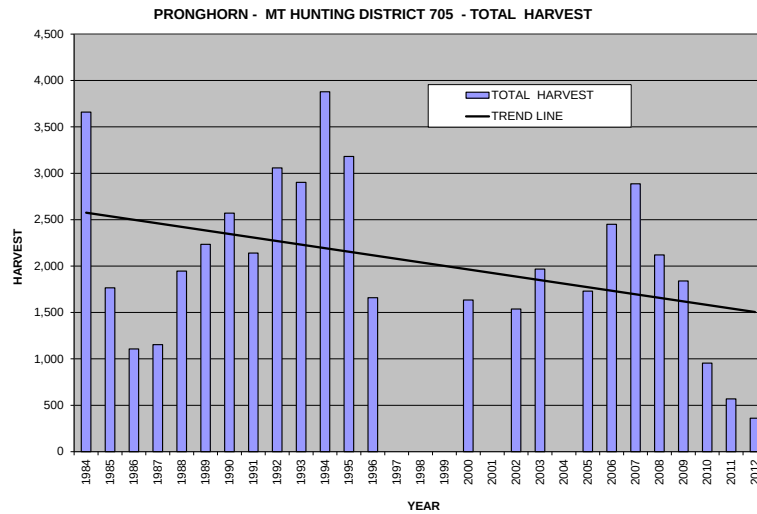


Fig. 60. Pronghorn – Montana hunting district 705 – total harvest

Hunter Numbers and Success Rates Total hunting pressure in the (for all seasons and methods of take) in the hunting district has varied from a high of 3,922 hunters in 1984 to a low of 550 hunters in 2012. The mean value for hunting pressure for the district is 2,119 hunters. The long-term trend for hunter numbers is declining.

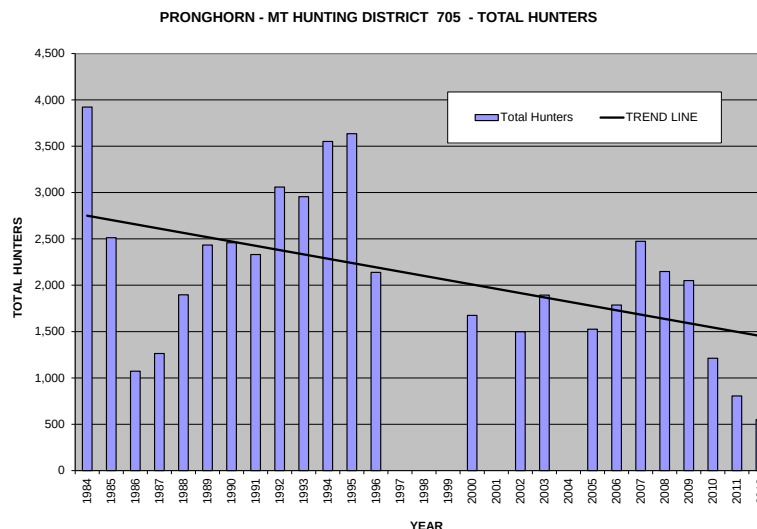


Fig. 61. Pronghorn – Montana hunting district 705 – total hunters

Hunter success rates in the hunting district have varied from a high of 137.2% in 2006 to a low of 65.6% in 2012. The mean value for hunter success rates in the hunting district is 95.7%. The long-term trend for hunter success rates is stable.

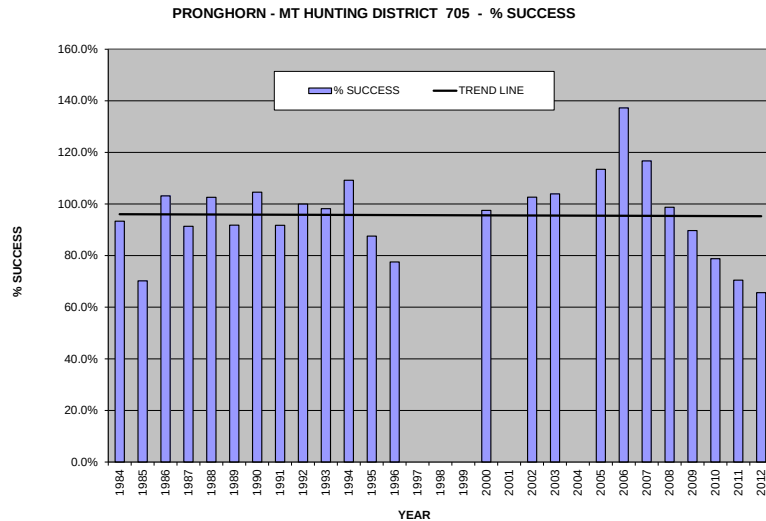


Fig. 62. Pronghorn – Montana hunting district 705 – hunter success rates

Summary of Herd Vital Statistics and Management Implications

An evaluation of an assortment of data for pronghorn in this hunting district indicates that it isn't performing at an optimum level. In addition, due to some conflicting data, it isn't totally clear what is happening with some of the estimates for the population parameters. Despite the ambiguity of the data the rating for this herd district should be fair.

- The data for the long-term trend for population size is ambiguous. The general information indicates the long-term trend for population size is increasing. Conversely, the data set for a shorter period of time from surveys of trend count areas indicates the long-term trend is decreasing.
- The long-term trend for young/100 female ratios is decreasing slightly. The young/100 female ratios reported for the hunting district are substantially higher than those reported for hunting district 204. The mean value for young/100 female ratios for hunting district 705 is 93:100 while the value for hunting district 704 is 29:100. Young/100 female ratios of 93:100 are very adequate for maintaining or increasing a pronghorn population.
- The long-term trend for harvest is decreasing. The total harvest of 361 animals reported for 2012 is the lowest value reported for 24 years of data for this hunting district. The reported harvest for 2012 is only 9.3% of the maximum harvest reported in 1994 (3,879 animals) and is only 17.6% of the mean value for harvest (2,055) for the hunting district. If the low harvest values are caused by something other than access issues or low numbers of limited licenses then this would be justification for rating the unit as poor overall instead of fair.

The upshot of all this information indicates that if current habitat conditions are maintained, the pronghorn population has the potential (due to high young/100 female ratios) to recover substantially in the near future. However, if habitat conditions deteriorate further due to development or adverse environmental conditions, recovery will be impeded or totally blocked. It is also interesting to note that this population doesn't appear to be able to sustain anywhere near the harvest it previously supported. This implies that winter mortality on fawns is substantial and that current winter range habitat is insufficient or cover or forage is inadequate.

SECTION IV

BIG GAME DATA AND ANALYSIS – WYOMING

Wyoming (WG&F) use a process called management by objective (MBO) to manage the big game resources of the state. Management by objective is an adaptation of a process originally described by Connolly (1981). A schematic for the Wyoming management by objective process is provided in figure 63.

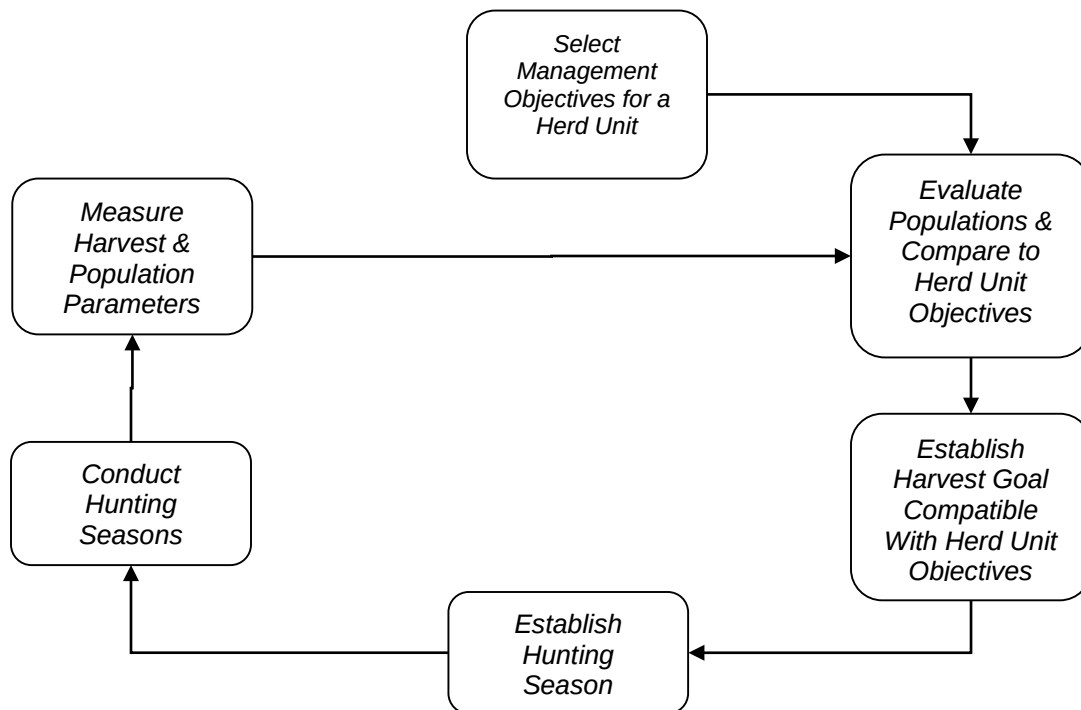


Fig. 63. Wyoming Game and Fish Management by Objective Process

As seen in the management by objective schematic, the first step of the MBO process is selecting management objectives for a herd occupying a specific herd unit. The primary objectives include goals for post-hunt population size and sex ratios (male/100 female ratios). The secondary objectives include the management strategies and tactics that will need to be used to achieve the primary objectives. For example, they may include limited licenses seasons which would be needed to achieve high male/100 female ratios if a herd unit has been selected as a trophy hunting unit. Secondary objectives may also suggest the need for projects such as habitat improvement to improve habitat carrying capacity or mitigate problems with game damage on private land.

After the first step of selecting management objectives is completed the MBO process becomes an annual cycle. This cycle includes data collection (measure harvest and population parameters), population analysis, formulating harvest goals, hunting season recommendations as well as conducting the hunting season. It is an adaptive management process that allows for adjustments in hunting seasons and harvest objectives in order to achieve or make progress towards stated objectives for population size and herd composition.

Wyoming uses a number of different techniques to collect biological information about big game herds. The agency spends a significant amount of effort conducting age and sex composition

surveys (A&SCS) for deer, elk and pronghorn. The surveys are post-hunt surveys for deer and elk and pre-hunt surveys for pronghorn.

Wyoming also uses line transect methodology to obtain census data for pronghorn. This technique is conducted using a fixed-wing aircraft and multiple observers to sample pronghorn populations. The data collected provides a statistically valid estimate of the size of pronghorn populations in selected herd units. This information is used as alignment data to validate population models for pronghorn throughout the state.

Wyoming uses a modification of the mail in post card survey for harvest surveys for deer, elk and pronghorn. Randomly selected license holders are sent a postcard requesting them to complete an internet harvest survey. Sample sizes adequate to meet objectives for accuracy and precision for resident and non-resident hunters are drawn from license data. Harvest estimates are developed for each hunt area and herd unit in the state for deer, elk and pronghorn. In addition, information on hunter success rates and number of days hunted are also obtained from the data.

Estimating abundance of wild animals inhabiting large geographic areas is a difficult task. Due to budget and time constraints it is not possible to conduct surveys to estimate density, herd composition and survival every year for all big game species in all herd units. However, management by objective requires that WG&F provide annual estimates of animal abundance (population size) for each herd unit that supports a hunting season. The annual regulation recommendation process requires that harvest objectives and numbers of limited licenses be calculated based on a comparison of the relationship of the population estimate to the long-term population objective. Therefore, wildlife managers are required to rely on computer simulation models to produce annual estimates of population size for many big game herds.

Models are abstractions of the real world based on assumptions and as such don't provide statistically valid estimates of population size and structure. However, in a less than perfect world, they provide an orderly process for compiling and analyzing data, which allows biologists to conduct numerous repetitions, or trials that hopefully reveals what is happening with the population in question. Real data is used in the models. Harvest, young to adult ratios, and survival estimates, when available are actual input parameters for the models. Other values such as initial population size, initial population structure, wounding loss and winter severity are estimated but are based upon a range of standard values developed through research. The model is "run" repeatedly until a result is achieved that reasonably aligns on observed, or in some years, estimated male to female ratios and population size. Wildlife agency recognizes the limitations of the modeling processes. As better information or techniques become available they will be adopted and used in the season setting process.

Included below is a map of the 5 mule deer herd units for northeast Wyoming. Hopefully this will aid the reader in understanding the juxtaposition of all the units instead of having to rely on maps of individual units which can be confusing at times.



Fig. 64. Northeastern Wyoming mule deer herd units

POWDER RIVER, MULE DEER HERD UNIT 319 (refer to appendix, table 7)

General Description Mule Deer Herd Unit 319 is located in Northeastern Wyoming and is commonly called the Powder River Herd Unit. The Herd Unit lies in portions of Sheridan, Johnson, Campbell and Crook Counties and contains 4 hunt areas; 17, 18, 23 and 26. The unit is bounded on the north by the Montana/Wyoming state line; on the east by D Road; and on the south and the west by Interstate Highway 90. The herd unit covers an area of approximately 4,719 square miles with 4,397 square miles of the unit considered to be occupied habitat. Elevation in the herd unit varies from a high of approximately 4,890 ft. along I-90 south of Sheridan to a low of approximately 3,390 ft. where the Powder River crosses the Montana/Wyoming state line.

The area consists of a rolling upland plain with low to moderate relief, broken by buttes, mesas, hills and ridges. The present day landforms of the area have been shaped mostly by the action of water. The drainages dissecting the area are incised, typically are ephemeral or intermittent, and do not naturally provide permanent or year-around sources of water along their entirety (BLM 2003). Major river valleys (Tongue, Powder and Little Powder Rivers) in the Herd Unit have wide, flat floors and broad floodplains.

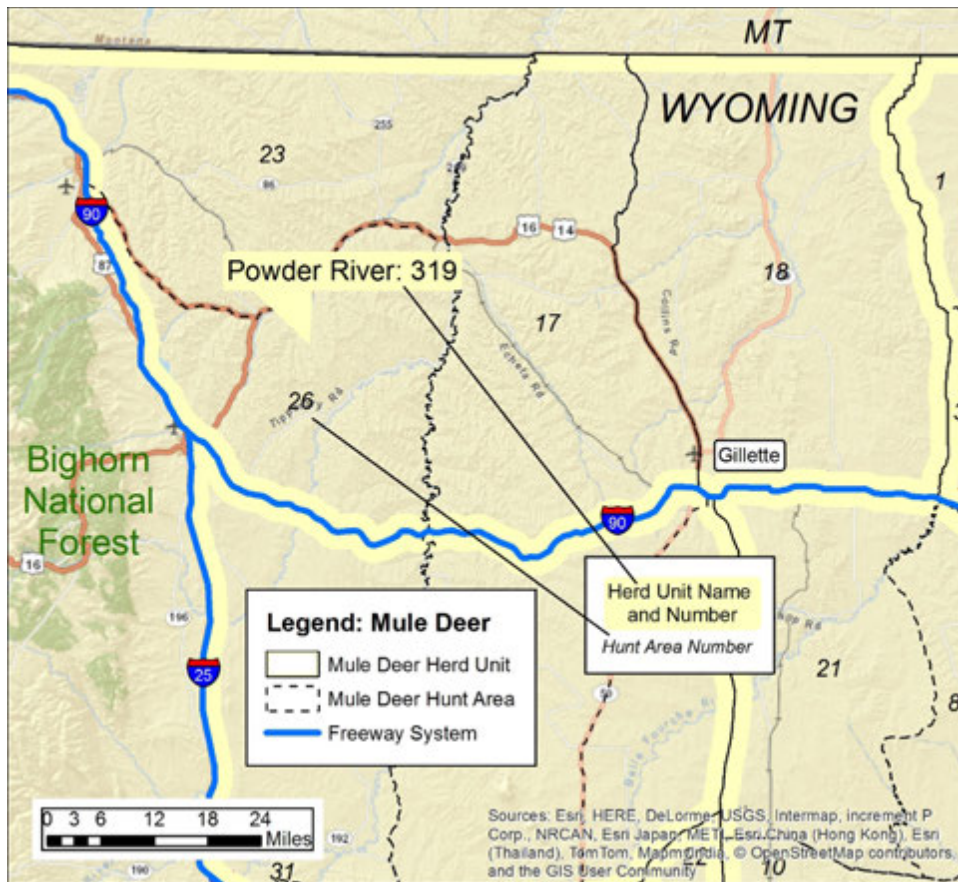


Fig. 65. Wyoming mule deer herd unit 319 (Powder River)

Vegetation in the herd unit include shortgrass prairie, sagebrush shrubland, mixed-grass prairie, coniferous forest, and other shrublands. These five plant communities account for approximately 93% of the land coverage with barren ground, wet meadow, agriculture, shrubby riparian, forest riparian, herbaceous riparian and urban/disturbed lands accounting for the remainder of the land coverage (BLM 2003).

Land Ownership The Herd Unit contains a mixture of public and private lands. The distribution of land ownership in the Herd Unit is approximately 78% private land, 14% federal land, and 8% state land. The portion of the Herd Unit that is in federal or state ownership is distributed as follows; Bureau of Land Management 55%, State of Wyoming 37%, Bankhead Jones Lands 6%, and National Grassland (USFS) 2% (WGFD 2014).

Land Use Much of the private and public land in the Herd Unit is used to graze livestock, primarily cattle. A relatively small portion of the area is plowed or planted to crops, primarily alfalfa, grass hay and winter wheat. Oil and gas development and coal mining are examples of mineral development and extraction that have occurred throughout the herd unit. Some of the largest coal strip mines in northeast Wyoming are located in the unit. Oil wells, conventional natural gas wells and coal-bed natural gas wells are numerous in the herd unit and are concentrated in the portion of the unit north and west of Gillette in the Little Powder River drainage. Urban and sub-urban development includes the communities of Gillette (29,087), Sheridan (17,444), Moorcroft (1,009), and Ranchester (855) (Together We Teach Education Resources 2014). The distribution of the remainder of the human population in the area is rural in character being dispersed in very small communities, settlements or individual ranches or home sites throughout the Herd Unit.

Management Issues This herd unit is managed as a recreational unit with unlimited buck licenses available for resident hunters and limited entry licenses available for hunting does and fawns. Population estimates for this deer herd are derived from population models based on reported harvest and observed sex and age ratio data. Independent estimates of deer density from aerial census surveys are not available for this herd unit (WGF 2013).

Population Size The deer population in Deer Herd Unit 319 has fluctuated substantially over the years, ostensibly due to the impacts of severe winters on deer survival. As it is currently represented, the minimum population estimate for this herd was 27,262 animals in 1986. The maximum population estimate for the herd was 66,513 animals in 1991. The mean value for the population for all years is 45,490 animals. Since the decline in the early 1990s, the deer population had again increased to an estimated 54,495 animals in 2005 but has since declined to approximately 35,300 in 2012. Despite the substantial population fluctuations, the long-term trend for population size is slowly increasing. A short-term trend for population size shows the population has decreased 33% since 2008. The long-term population objective for this herd is 52,000 animals.

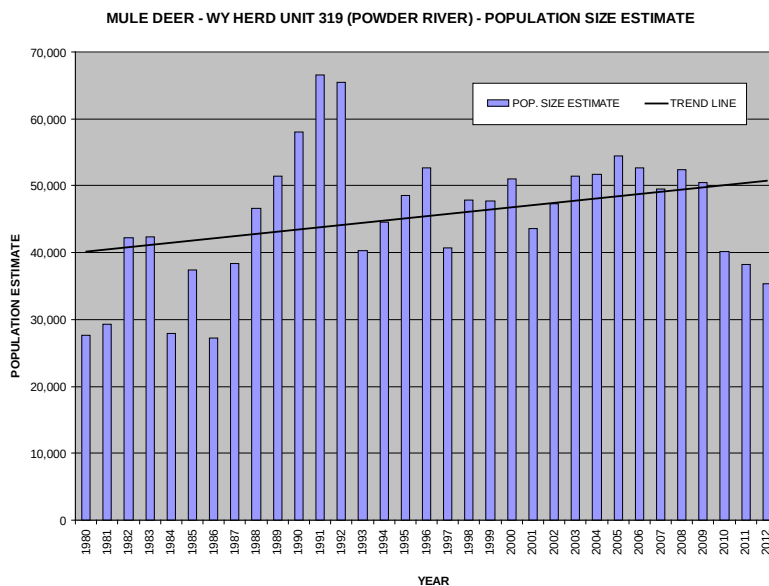


Fig. 66. Mule deer – Wyoming herd unit 319 (Powder River) - population Size

Age and Sex Composition

Male/100 female ratios have varied from a low of 19 males/100 females in 1980 to a high of 43 males/100 females in 2006. The mean for all years of data is 31 males/100 females. The overall trend for all years of data shows male/100 female ratios increasing.

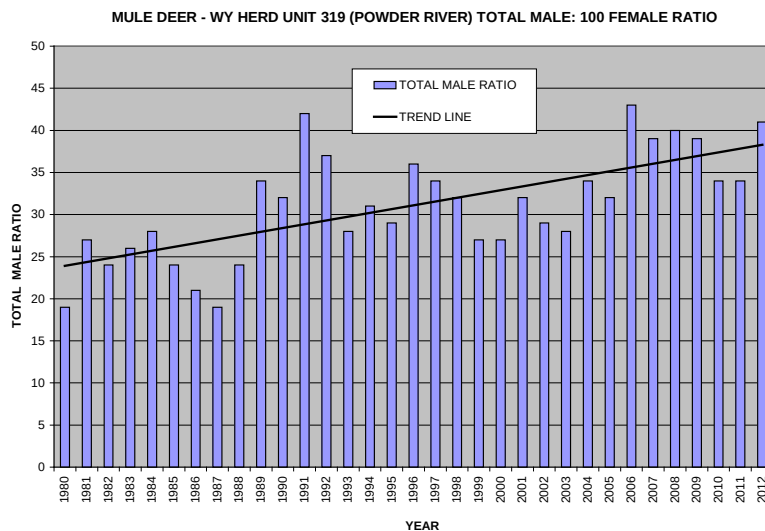


Fig. 67. Mule deer – Wyoming herd unit 319 (Powder River) - males/100 female ratios

Young/100 female ratios have ranged from a high of 101 young/100 females in 1981 to a low of 43 young/100 females in 1986 and again in 2001. The mean value for all years is 68 young/100 females. The trend for young/100 female ratios for all years of data is decreasing.

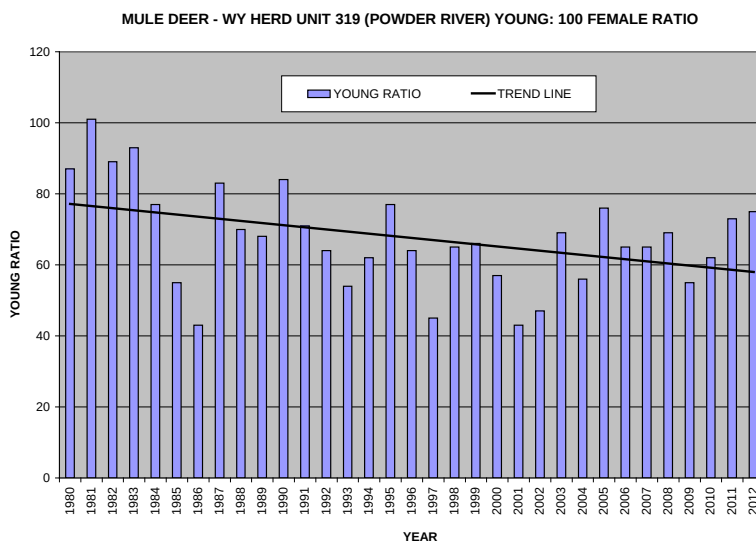


Fig. 68. Mule deer – Wyoming herd unit 319 (Powder River) - young/100 females ratios

Harvest

Male harvest for this herd unit has ranged from a high of 5,477 animals in 1983 to a low of 1,716 animals in 2011. The mean for male harvest for all years of data is 3,191 animals. There have been two main peaks of harvest for this herd in the 1980s and again in the 1990s (5,477 males in 1983 and 4,291 males in 1992). Also, examining means of harvest by decade shows a significant decline in male harvest from a mean of 3,755 males harvested in the 1980s to a mean of 1,952 males harvested in the 2010s, a decrease of approximately 48%. Since the early 1990s, male harvest has never approached the years of peak harvest in the 1980s. The long-term trend for male deer harvest is decreasing.

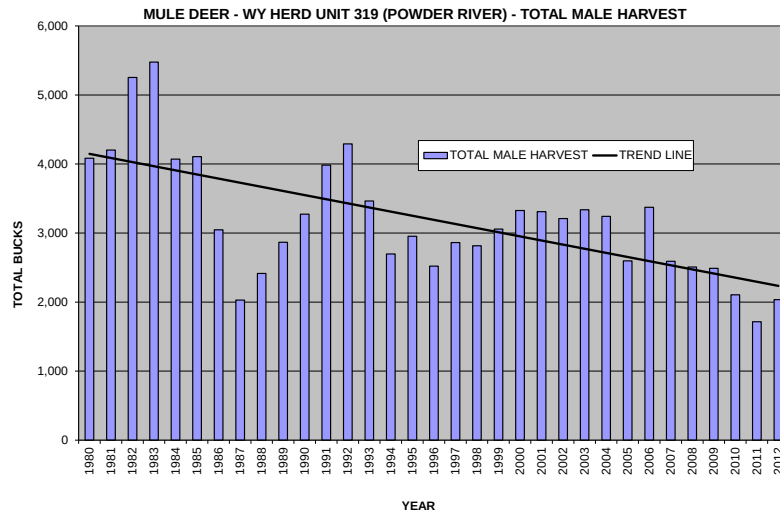


Fig. 69. Mule deer – Wyoming herd unit 319 (Powder River) – male harvest

Total harvest for this herd unit has ranged from a high of 8,463 animals in 1983 to a low of 2,028 animals in 1987. The mean of total harvest for the period 1980 to 2013 is 4,155 deer. The trend for total deer harvest for all years of data is decreasing. As with male harvest, the long-term trend for total deer harvest is decreasing.

Antlerless harvest has ranged from a low of 0 does and fawns harvested in 1987 to a high of 2,999 harvested in 1992. Mean antlerless harvest for 1980 through 2012 is 964 animals. Through all the years of data, antlerless harvest has made up approximately 23% of the total harvest. During the years of peak harvest in the herd unit antlerless harvest comprised as much as 35% of the total harvest in 1983 and 41% of the total harvest in 1992.

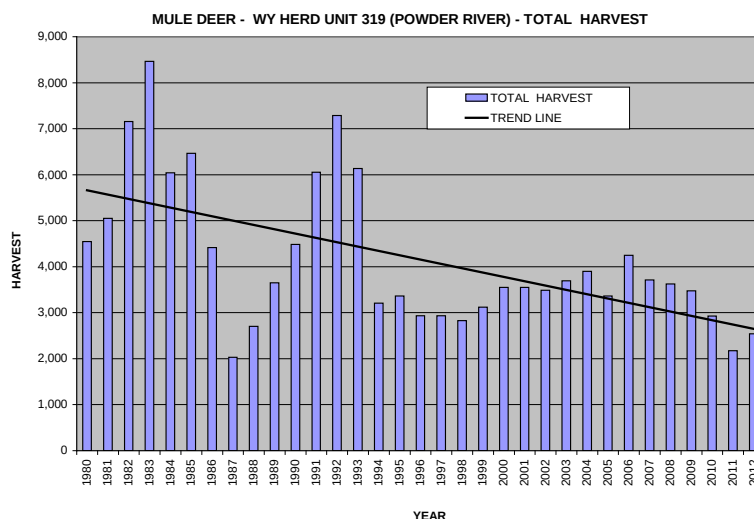


Fig. 70. Mule deer – Wyoming herd unit 319 (Powder River) - total harvest

Hunter Numbers and Success Rates

Total hunting pressure (all seasons and methods of take) has ranged from a high of 10,980 hunters in 1983 to a low of 2,028 hunters in 1987. This herd unit has supported an average of 5,826 hunters per year for all years of data. The overall trend for hunter numbers is decreasing

and an examination of hunter numbers by decade shows a substantial decrease with the mean of hunter numbers in the 2010s (3,952) equaling only 46% of the mean for hunter numbers in the 1980s (7,229). Antlered deer licenses for resident hunters have been unlimited in number while antlerless deer hunting licenses have been limited in number for all years of the analysis.

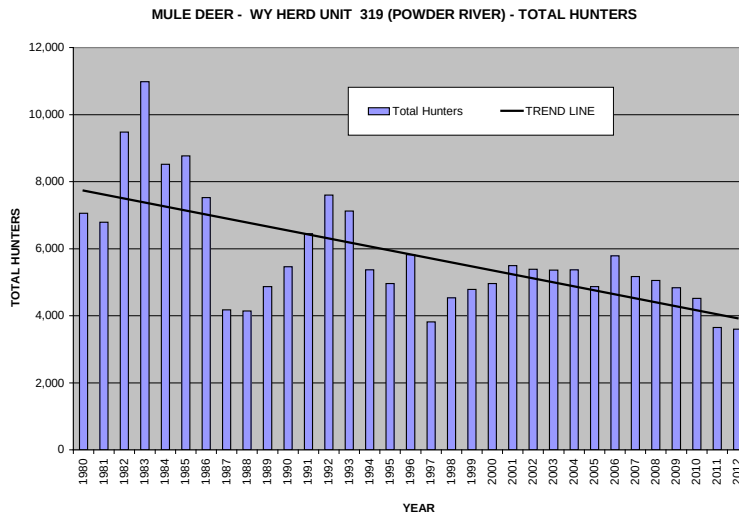


Fig. 71. Mule deer – Wyoming herd unit 319 (Powder River) – total hunters

Hunter success rates for all methods of take have varied from a low of 48.6% in 1987 to a high of 95.9% in 1992. The mean for hunter success rates for all years of the analysis is 70.3% for all methods of take. The overall trend for hunter success rates is level and an examination of hunter success rates by decade shows only a moderate decrease in hunter success from the high in the 1990s of 74% success to the 64.9% success rate for the 2010s.

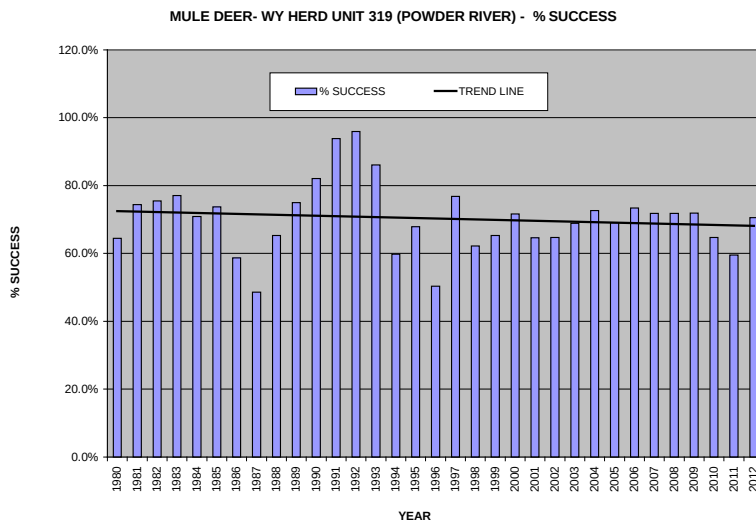


Fig. 72. Mule deer – Wyoming herd unit 319 (Powder River) - hunter success rates

Summary of Herd Vital Statistics and Management Implications

An evaluation of a variety of data for the mule deer herd in this herd unit indicates that it is not performing at an optimum level. According to an evaluation system that was developed for this project, the performance rating for this herd would be fair for the following reasons:

- The mule deer population in this herd unit is substantially below the long term population objective (LTO) set by the Wyoming Game and Fish Department (35,300

versus and LTO of 52,000 animals). The last time this deer herd was at objective was 2008. However, this herd has been at objective or within 10% of the object for 7 of the past 10 years.

- A lone bright spot in the data for this herd unit is the long-term trend for population size for the herd is increasing. However, in the short term (last 4 years) this population has steadily decreased. Even under the best of circumstances it will likely take a few years for this short-term trend to reverse itself and see the population begin to build back to the long-term population objective.
- The long-term trend for young/100 female ratios is decreasing. However, young/100 female ratios for the last 2 years have been above the mean value for young/100 female ratios (73:100 and 75:100 respectively versus 68:100). If this short-term trend for young/100 female ratios continues there is potential for reversing the short-term trend of population decline.
- Another negative factor for this deer herd is a decreasing long-term trend for harvest. The total harvest of 2,541 animals in 2012 is the third lowest harvest recorded in the 32 year period of this data analysis. Furthermore, the harvest estimate for the last 6 years has been below the long-term mean for harvest (4,155 animals) for this herd unit.

Following are some additional observations and comments about the deer herd in this herd unit. Buck harvest and antlerless harvest, with the exception of a couple years in the last decade, have been conservative and the population is barely able to stay at the long-term population objective. Even with a gradual increase in male/female ratios, young/female ratios are slowly declining which is contrary to the popular belief of sportsmen that high male/female ratios insure high fawn production and recruitment. A multitude of factors besides male/female ratios can influence young/female ratios such as weather, habitat, disease and predation. If trends for population size and recruitment of young continue to decrease it is likely an indication that carrying capacity of the habitat for this herd is decreasing, as a decrease in population size or density usually results in an increase of young production if the habitat is in good condition.

The upshot of all of this information is that if current habitat conditions are maintained, and if the short-term trend for young/100 females continues, this deer herd will likely show a gradual improvement in population size and harvest. However, when a deer herd is performing marginally, it is likely that any habitat loss or degradation will have a negative impact on the population. Therefore, any further development slated for the area, unless it is carefully planned and timed to avoid deer habitat, will likely have a negative impact on the population.

PUMPKIN BUTTES, MULE DEER HERD UNIT 320 (refer to appendix, table 8)

General Description Mule Deer Herd Unit 320 is located in Northeastern Wyoming and is commonly known as the Pumpkin Buttes Herd Unit. This herd unit lies in portions of Campbell, Johnson and Natrona counties and contains 4 hunt areas; 19, 20, 29 and 31. The herd unit is bordered on the north by Interstate Highway 90; on the east by Wyoming State Highway 59; on the south by Wyoming State Highway 387 and on the west by Interstate Highway 25. The herd unit covers an area of approximately 2,711 square miles, all of which is considered occupied habitat (WGFD 2014). Elevation in the herd unit varies from a high of approximately 6,049 feet at North Butte southwest of Savegeton to a low of approximately 4,500 feet where the Powder River crosses Interstate Highway 90.

The geography of the area is similar in appearance to Herd Unit 319 (Powder River) to the north being a rolling upland plain punctuated by buttes, mesas, hills and ridges. Vegetation types or plant communities in the herd unit include shortgrass prairie, sagebrush shrubland, mixed grass prairie, coniferous forest and other shrublands. As in the Powder River Mule Deer Herd Unit, these 5 plant communities account for approximately 93% of the land coverage (BLM 2003).



Fig. 73. Wyoming mule deer herd unit 320 (Pumpkin Buttes)

Land Ownership Land ownership in this herd unit is mixed with approximately 81% private land, 13.2% federal land (Bureau of Land Management) and 5.8% state land (WGFD 2013).

Land Use Livestock grazing is a major land use in the area while only a small portion of the area is plowed or planted to crops such as alfalfa, grass hay or winter wheat. Extraction of natural resources for energy development is a major activity in this herd unit. There are a number of large coal strip mines in the east portion of the herd unit. Drilling for oil, natural gas and coal-bed methane is another large industry in this area with numerous wells, processing and compressor plants, pipelines and service roads existing in the unit. Communities in the herd unit include Gillette (29,087), Buffalo (4,585), Midwest (404), Kaycee (203) and Edgerton (201). The distribution of the remainder of the human population in the herd unit is rural in character being dispersed in very small communities, settlements or individual ranches or farms.

Management Issues The Pumpkin Buttes Mule Deer Herd Unit has a post-season population objective of 11,000 deer. The management strategy is recreational management. The objective and management strategy were last revised in 1988 but are being reviewed this spring. This herd unit is largely private land with limited areas of accessible public lands. Limiting hunting on public lands to antlered deer helps maintain hunting recreation for those unable or unwilling to access private lands. Coalbed methane gas development has slowed after 10 years of intense development in Areas 19 and 20 and the northeast portion of Area 29. Interest in deep oil is increasing at this time. Publicly accessible BLM and state lands in the northern portions of Areas 19 and 29 are particularly problematic as intensive development activity has reduced quality hunting opportunity. In recent years these lands attracted fewer hunters (WGFD 2013).

Population Size The deer population in Deer Herd Unit 320 fluctuated substantially in the 1980s, presumably due to severe winter weather, but since that time the population has stabilized and population changes have been more gradual. The current depiction of the population shows a maximum population estimate for the herd as 15,723 animals which occurred in 1982. The minimum estimate for population size is 6,713 animals and occurred in 1987. The mean value for the population for all years is 11,117 animals. The 2012 estimate for population size is 9,600 animals. Since the population decline in the late 1980s the deer herd has increased and remained fairly stable. In the years since the low population size in 1987 the herd has been at or above 10,000 animals for 19 of the 24 years and only recently has the population dropped below 10,000 animals again. Even with the population fluctuations in the 1980s the long-term trend for population size is stable. The long-term population objective for the herd is 13,000 animals.

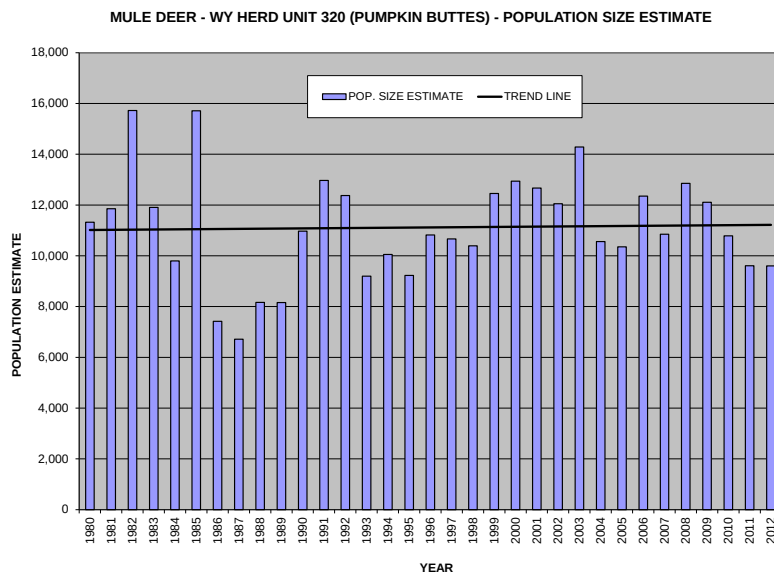


Fig. 74. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – population size estimate

Age and Sex Composition Male/100 female ratios have varied from a low 18 males/100 females in 1981 to a high of 53 males/100 females in 2009. The mean for all years of data is 33 males/100 females. The overall trend for all years of data shows male/100 female ratios increasing.

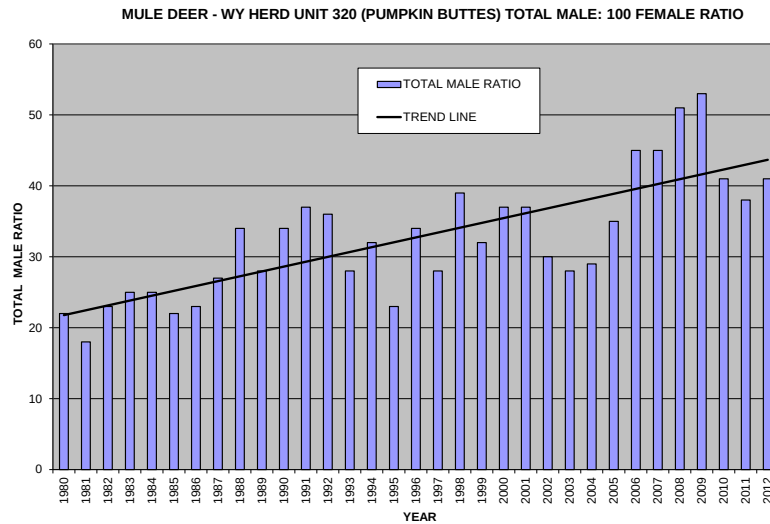


Fig. 75. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – male/100 female ratios

Young/100 female ratios have ranged from a high of 104 young/100 females in 1987 to a low of 36 young/100 females in 2001. The mean value for all years is 69 young/100 females. The long-term trend for all years of data for young/100 females is decreasing.

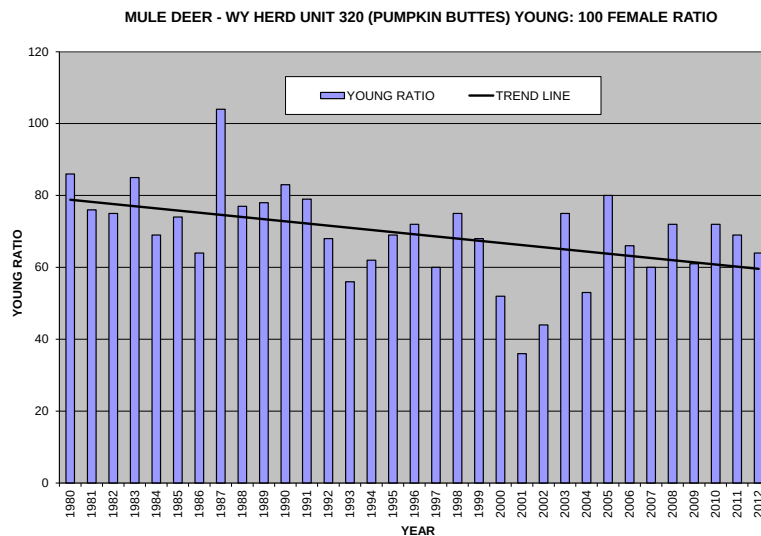


Fig. 76. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – young/100 female ratios

Harvest Total male harvest for this herd unit has ranged from a high of 1,229 bucks in 1983 to a low of 326 bucks in 1987. The mean value for male harvest for all years of the analysis is 729 bucks. The long-term trend for buck harvest is declining. A review of buck harvest by decade shows the 1990's with the highest average harvest per year for the decade of 795 bucks per year. Buck harvest has declined since the 1990s to an average of 555 bucks harvested per year for the 2010s, a decline of approximately 30% in buck harvest. Buck harvest for 2012 was 633 animals. Buck harvest for this herd unit has not equaled or exceeded the average buck harvest for the unit since 2003.

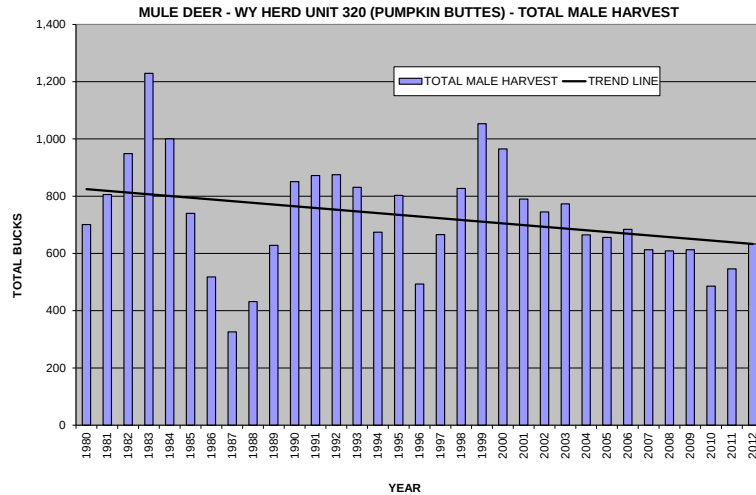


Fig.77. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – male harvest

Total annual harvest for this herd unit has ranged from a high of 1,484 animals in 1984 to a low of 427 animals in 1987. The mean of total harvest for all years from 1980 to 2012 is 925 animals. There appears to be 3 major peaks of harvest for this herd unit, the first occurring in 1984 (1,484 deer), a second in 1992 (1,346 deer harvested) and a third in 1999 (1,186 deer harvested). Total deer harvest for this herd unit hasn't exceeded 1,000 animals since 2000. Prior to 2001, total deer harvest had exceeded 1,000 animals in 9 of 21 years. Examining means of harvest by decade shows a peak in the 1990s followed by a decline in the following 2 decades. The trend for total harvest for all years of data is decreasing.

Antlerless (does and fawns) harvest has occurred in this unit for all years of this analysis and has ranged from a high of 484 animals in 1984 to a low of 54 animals in 1996. The mean antlerless harvest for all years of data is 196 animals. From 1980 to 2012, antlerless harvest has accounted for 21% of the total deer harvest in the herd unit. During the years of peak harvest, antlerless animals comprised nearly 33% of the total harvest in 1984, 35% of the harvest in 1992 and 11% of the total harvest in 1999.

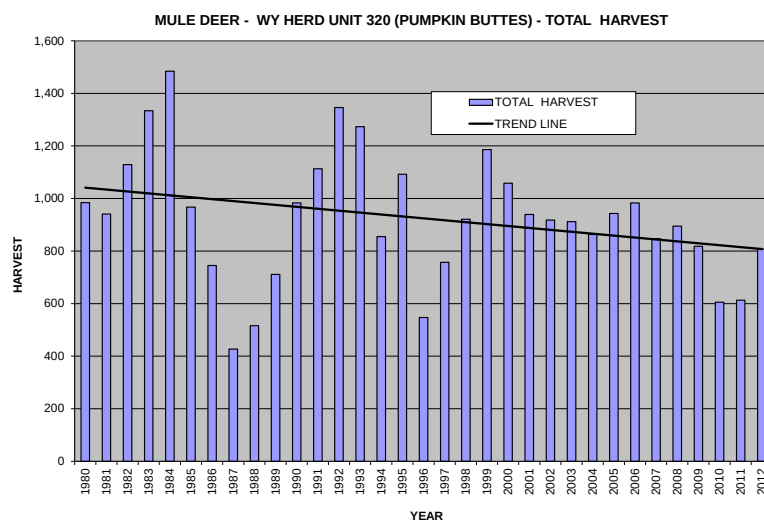


Fig. 78. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – total harvest

Hunter Numbers and Success Rates Total numbers of hunters for all seasons and methods of take has ranged from a high 2,464 hunters in 1984 to a low of 835 hunters in 1988. The mean number of hunters supported by this herd unit for all years of data is 1,467. The overall trend for hunter numbers is decreasing. Upon examining hunter pressure by decade, there is a gradual decrease in hunter numbers with the total number of hunters in the 2010s equaling only 61% of the hunters that utilized the area in the 1980s (1,010 versus 1,658).

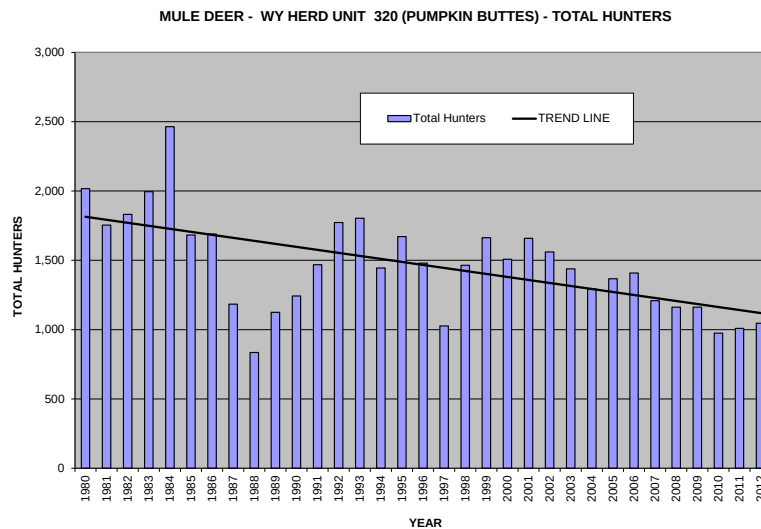


Fig. 79. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – total hunters

The overall trend for hunter success rates is increasing in this unit. Hunter success rates for all hunting methods and season of take has varied from a low of 36.1% in 1987 to a high of 79.1% in 1990 (there must have been a dramatic difference in population size of hunting season conditions for these two years as the number of hunters are almost identical (1,184 in 1987 compared to 1,243 in 1990)).

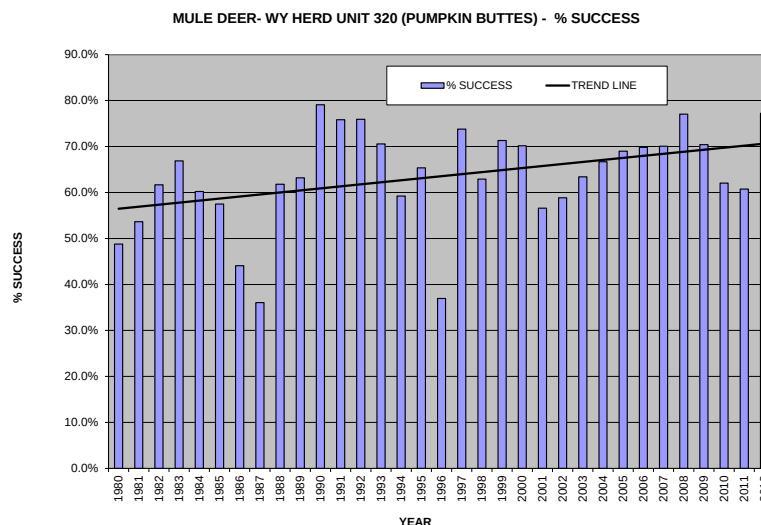


Fig. 80. Mule deer – Wyoming herd unit 320 (Pumpkin Buttes) – hunter success rates

Summary of Herd Vital Statistics and Management Implications An evaluation of an assortment of data for the mule deer herd in this herd unit indicates that it is not performing at an optimum level. According to the evaluation system that was developed for this project, the performance rating for this herd would be poor for the following reasons:

- The mule deer population in this herd unit is substantially below the long term population objective set by the Wyoming Game and Fish Department (9,600 versus 13,000 animals). The last time this deer herd was at objective was 2003. This herd has been at objective or within 10% of the object for only 4 of the past 10 years.
- The long-term trend for population size for the herd is stable. However, in the short term (last 3 years) this population has declined. Even under the best of circumstances it will likely take a few years for this short-term trend to reverse itself and see the population begin to build back to the long-term population objective.
- The long-term trend for young/100 female ratios is decreasing. However, young/100 female ratios for the last 5 years have equaled or exceeded the mean value for young/100 female ratios (69:100). If this short-term trend for young/100 female ratios continues the population may be able to stabilize and avoid further declines.
- Another negative factor for this deer herd is a decreasing long-term trend for harvest. The total harvest of 808 animals in 2012 is the sixth lowest harvest recorded in the 32 year period of this data analysis. Furthermore, the harvest estimate for the last 6 years has been below the long-term mean for harvest (925 animals) for this herd unit.

The end result of all of this information is that even if current habitat conditions are maintained, and if the short-term trend for young/100 females continues, this deer herd is unlikely to show any improvement in population size and harvest. However, if habitat conditions deteriorate due to development or adverse natural environmental conditions, population size and harvest will likely decline further than the current situation.

CHEYENNE RIVER, MULE DEER HERD UNIT 740 (refer to appendix, table 9)

General Description Mule deer herd unit 740 is located in northeastern Wyoming and is commonly referred to as the Cheyenne River herd unit. This herd unit lies in portions of Crook, Campbell, Weston, Converse and Niobrara counties and contains 9 mule deer hunt units (7, 8, 9, 10, 11, 12, 13, 14 and 21). The herd unit is bounded on the north by Interstate Highway 90 and US Highway 16; on the east by the South Dakota state line; on the south by US Highway 20 and Interstate Highway 25 and on the west by Wyoming State Highway 59. The herd unit covers a total area of approximately 6,429 square miles of which 6,101 square miles is considered occupied habitat (WGFD 2014). Elevation in the herd unit varies from a high of approximately 4,500 feet near Mule Shoe Junction to a low of 4,120 feet near Lusk.

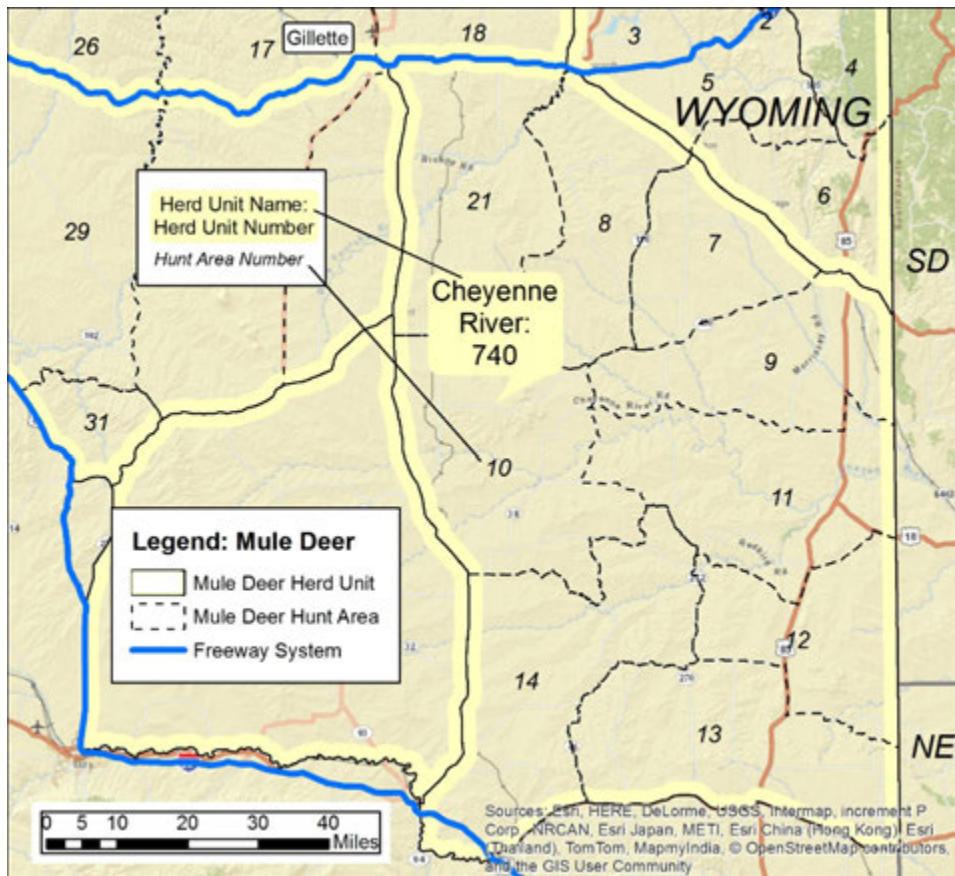


Fig. 81. Wyoming mule deer herd unit 740 (Cheyenne River)

Habitat in the herd unit consists of sagebrush steppe and sagebrush grasslands with rolling hills covered in ponderosa pine and limber pine woodlands in the western, central and northern portions of the herd unit (Wyoming game and fish). Habitat in the eastern portions of the herd unit consists of short grass prairie interspersed with the previously mentioned pine covered rolling hills (WGFD 2013). Rolling hills and ridges with an over-story of ponderosa pine and limber pine (*Pinus flexilis*) dominate the southern portions of the herd unit. Several major cottonwood riparian drainages traverse the herd unit including the Belle Fourche River and Cheyenne Rivers and their tributary creeks such as Beaver Creek, Lightning Creek, Twenty-Mile Creek, Lance Creek, and Old Woman Creek. Over-story vegetation along these drainages is dominated by decadent stands of plains cottonwood (*Populus deltoides*). The majority of drainages are ephemeral, and free flowing springs are rare (WGFD 2013).

Land Ownership Land status in the herd unit is predominately private, with this category accounting for 76% of the land in the unit. State lands, BLM, Forest Service National Grasslands, Bankhead/Jones lands and traditional forest service lands, in descending order, account for the remaining 24% of the land in the herd unit (WGFD 2014).

Land Use Agriculture in the form of livestock grazing is a very prominent land use in the herd unit. Agricultural crops grown in the area include winter wheat, grass and alfalfa hay but account for only a small percentage of the total area of the herd unit. Croplands are localized and found primarily southeast of Gillette, near Moorcroft, Upton, Newcastle, Manville, and Lusk. Energy development is another prominent land use in the area. The majority of oil and gas development occurs in the western and north central portions of the herd unit. However, substantial new oil and gas development is occurring in the central portions of the herd unit in northwest Niobrara

County (HA 11) and significantly increased development is occurring near Douglas (HA 14). There are several large surface coal mines in HA 10 and HA 21, which create a high level of disturbance. In addition, coal bed methane development over a large portion of these same two hunt areas is expected to continue to increase disturbance (WGFD 2013). Urban and suburban development include the communities of Gillette (29,087), Moorcroft (1,009), New Castle (3532), Douglas (6,120) and Lusk (1,567) (TWTER 2014). The remainder of the human population in the herd unit is rural in character, being dispersed in very small communities or individual ranches or farms throughout the area.

Management Issues The Cheyenne River mule deer herd unit was created in 2009 by combining the Thunder Basin and Lance Creek herds. The herd is managed for recreational hunting. Hunter access is largely limited and controlled by private landowners, and access fees along with outfitted hunting are common. Consequently, hunting pressure can be heavy on accessible public land. About two-thirds of the hunters pursuing mule deer in this herd unit are nonresidents. Hunt Areas (HA) 8, 10, and 13 are the only areas containing large blocks of accessible public land, which most of the resident hunters seek. These hunt areas typically receive heavy hunting pressure throughout the season (WGFD 2013).

Population Size The deer population in this herd unit has fluctuated substantially throughout the years of the analysis. As the population is currently represented, the minimum population estimate for the herd was 14,600 animals in 1986 as opposed to the maximum population estimate of 42,311 animals in 2000. The mean value for population size for all years of the analysis is 29,150 deer. The population estimate for 2012 is 17,367 animals. The most recent high population estimate for this herd was 39,922 animals in 2007. Since that time the population has declined to 17,367 animals in 2012, which is only 44% of the 2007 deer population estimate. Despite the recent decline in population size, the long term trend for population is increasing. The long-term population objective for this deer herd is 38,000 animals.

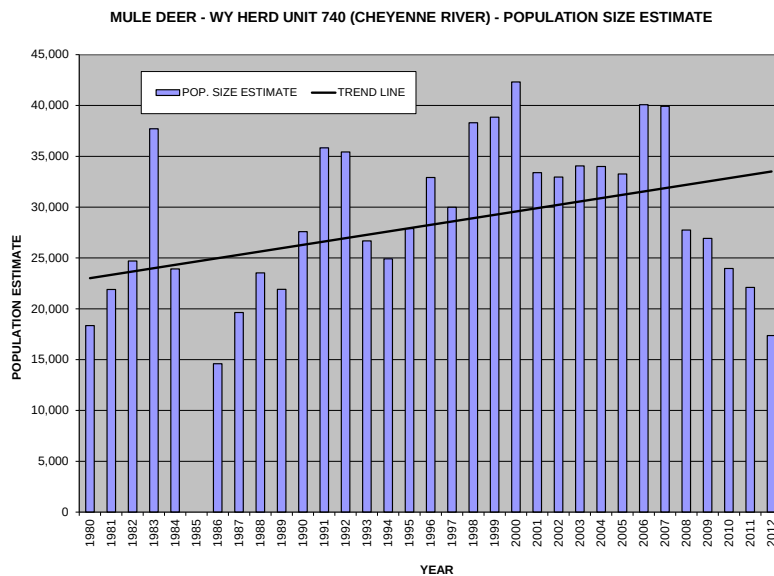


Fig. 82. Mule deer – Wyoming herd unit 740 (Cheyenne River) – population size estimates

Age and Sex Composition Males/100 female ratios for this unit have fluctuated from a low of 15 bucks/100 does in 1986 to a high of 45 bucks/100 does in 2007. The mean for all years of data in the analysis is 29 bucks/100 females. The overall trend for males/100 female ratios is increasing.

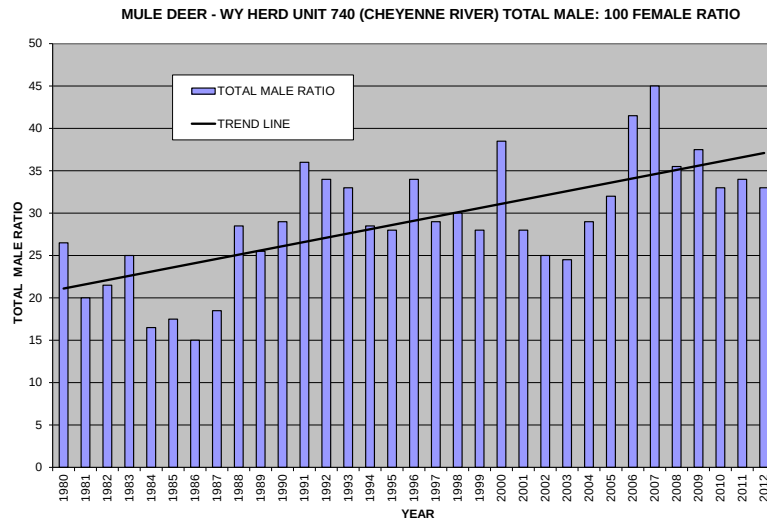


Fig. 83. Mule deer – Wyoming herd unit 740 (Cheyenne River) – male/100 female ratios

Young/100 female ratios have ranged from a high of 102 fawns/100 does in 1990 to a low of 44 fawns/100 does in 2012. The mean value for all years of the analysis is 74 fawns/100 females. The trend for young/100 female ratios is decreasing.

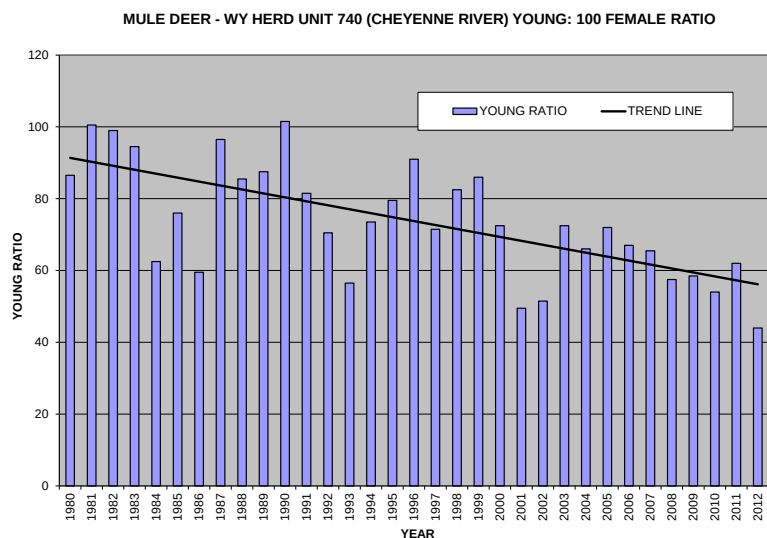


Fig. 84. Mule deer – Wyoming herd unit 740 (Cheyenne River) – young/100 female ratios

Harvest Total male harvest in this herd unit is varied from a low of 1,126 animals in 1987 to a high of 4,582 animals in 1992. The average buck harvest for all years of the analysis is 2,339. The long-term trend for buck harvest is declining. A review of average buck harvest by decade shows that the 1990s had slightly higher harvest than the 1980s (2,660 compared to 2,486), but buck harvest by decade has steadily declined since that time to 1,317 bucks harvest per year in the 2010s, just 50% of what the harvest was in previous decades. Buck harvest in this herd unit hasn't exceeded the average harvest for the herd unit since 2002.

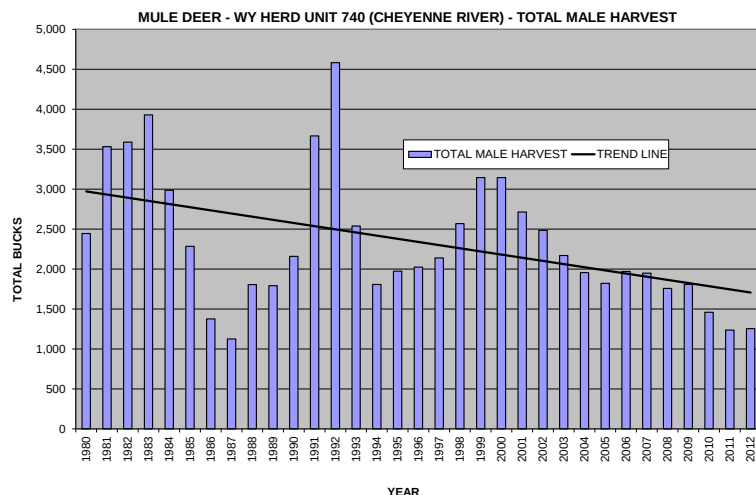


Fig. 85. Mule deer – Wyoming herd unit 740 (Cheyenne River) – male harvest

Total number of animals harvested in this herd unit has ranged from a low of 1,302 animals in 1987 to a high of 7,127 animals in 1992. The mean for total harvest for all years of the analysis is 3,267 animals. The long-term trend for total deer harvest for all years of the analysis is declining. Examining means of harvest by decade shows a dramatic decrease in harvest since the 1990s. The mean harvest for the 2010s is less than half the harvest that occurred in the 1990s. The total harvest of 1,346 animals for 2012 is the second lowest harvest that has occurred in this herd unit (lowest harvest was 1,302 animals in 1987).

Antlerless harvest (does and fawns) has occurred in this herd unit in all years of the analysis and has accounted for a substantial percentage of total harvest in the early to mid-1980s as well as the early 1990s. The harvest of 2,292 animals in 1985 was 50% of the total harvest and the harvest of 2,545 animals in 1992 was 35.7% of the total harvest.

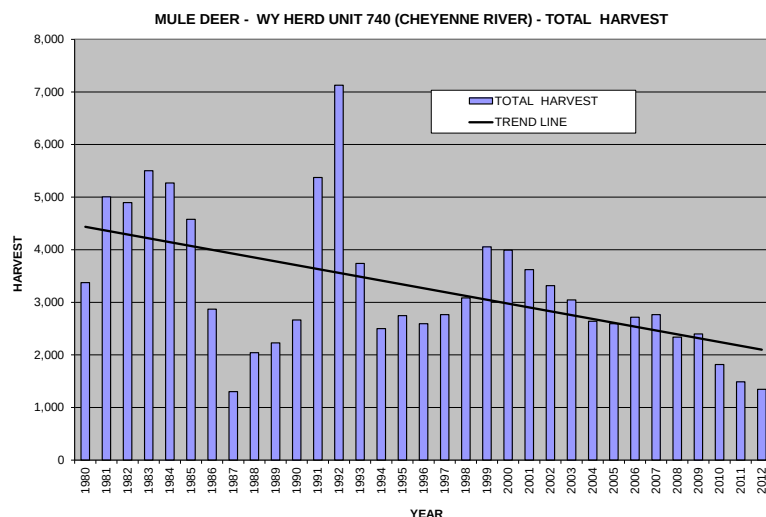


Fig. 86. Mule deer – Wyoming herd unit 740 (Cheyenne River) – total harvest

Hunter Numbers and Success Rates Total hunting pressure for all seasons and methods of take has ranged from a high of 7,727 in 1984 to a low of 2,511 in 2012. The average number of hunters supported by the herd unit over the years is 4,719. The long-term trend for hunter numbers is decreasing. An examination of hunter numbers by decade demonstrates that there is

a significant decline with the 2010s supporting approximately half the number of hunters that utilized the area in the 1980s (5,450 versus 2,511). The long-term trend for numbers of total hunters in the unit is decreasing.

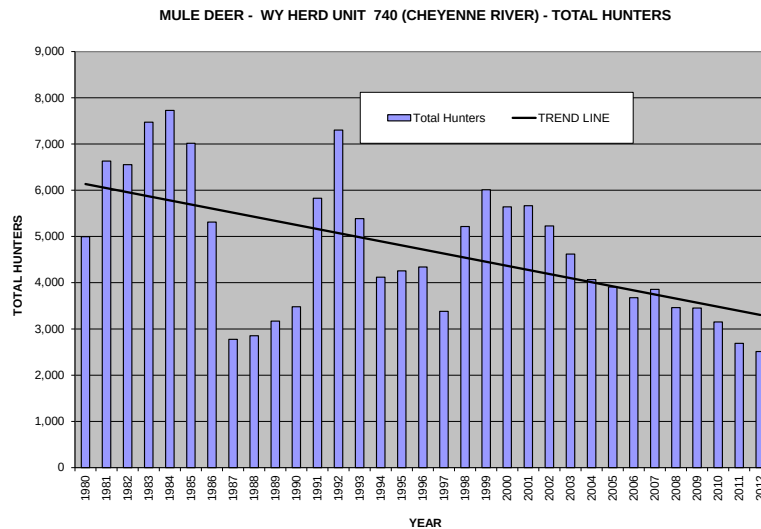


Fig. 87. Mule deer – Wyoming herd unit 740 (Cheyenne River) – total hunters

Hunter success rates for all seasons and methods of take have varied from a low of 47% in 1987 to a high of 98% in 1992. The mean for hunter success rates for all years of data is 68%. The overall trend for success rates is only slightly decreasing. Hunter success rates peaked in the 1990s at 73% success and have declined by about 15 percentage points in the 2010s

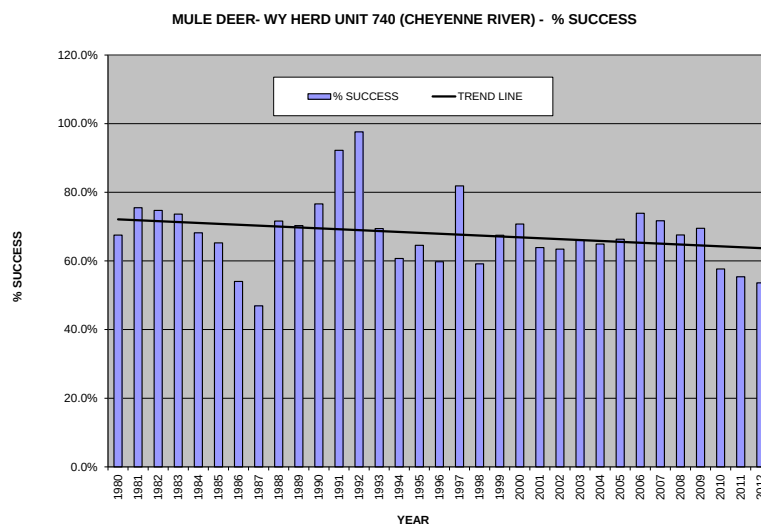


Fig. 88. Mule deer – Wyoming herd unit 740 (Cheyenne River) – hunter success rates

Summary of Herd Vital Statistics and Management Implications An evaluation of a variety of data for the mule deer herd in this herd unit indicates that it is not performing at an optimum level. According to the evaluation system that was developed for this project, the performance rating for this herd would be poor for the following reasons:

- The mule deer population in this herd unit is substantially below the long term population objective set by the Wyoming Game and Fish Department (17,367 versus 38,000 animals). The last time this deer herd was at objective was 2007. This herd has been at objective or within 10% of the object for only 2 of the past 10 years.

- The long-term trend for population size for the herd is increasing. However, in the short term (last 6 years) this population has been declining. Even under the best of circumstances it will likely take a few years for this short-term trend to reverse itself and see the population begin to build back to the long-term population objective.
- The long-term trend for young/100 female ratios is decreasing. The last time young/100 female ratios met or exceeded the mean value for young/100 females for this herd unit (74:100) was 14 years ago (1999). Unless young/100 female ratios improve for this deer herd it is unlikely that the population will make any progress towards the long-term objective for population size.
- Another negative factor for this deer herd is a decreasing long-term trend for harvest. The total harvest of 1,346 animals in 2012 is the second lowest harvest recorded in the 32 year period of this data analysis. Furthermore, the harvest estimate for the last 10 years has been below the long-term mean for harvest (3,267 animals) for this herd unit.

The end result of all of this information is that even if current habitat conditions are maintained, and if the short-term trend for young/100 females continues, this deer herd is unlikely to show any improvement in population size and harvest. However, if habitat conditions deteriorate due to development or adverse natural environmental conditions, population size and harvest will likely decline further than the current situation.

BLACK HILLS, MULE DEER HERD UNIT 751 (refer to appendix, table 10)

General Description Mule deer herd unit 751 is located in northeastern Wyoming and is commonly recognized as the Black Hills herd unit. The herd unit lies in portions of Crook and Weston counties and contains 6 hunt areas; 1, 2, 3, 4, 5 and 6. The unit is bounded on the north by the Montana state line; on the east by the South Dakota state line; on the south by US Highway 16 and on the west by D road and Rocky Point road. Vegetation in the herd unit is diverse. Ponderosa pine is the dominant overstory species on forested lands. Quaking aspen, paper birch, and bur oak stands are present. Important shrubs include big sagebrush and silver sage, Saskatoon serviceberry, Oregon grape, common chokecherry, spirea, and true mountain mahogany. Many non-timbered lands in the herd unit are dominated by sagebrush or are used to produce agricultural crops such as winter wheat, alfalfa hay, and grass hay (WGFD 2013).

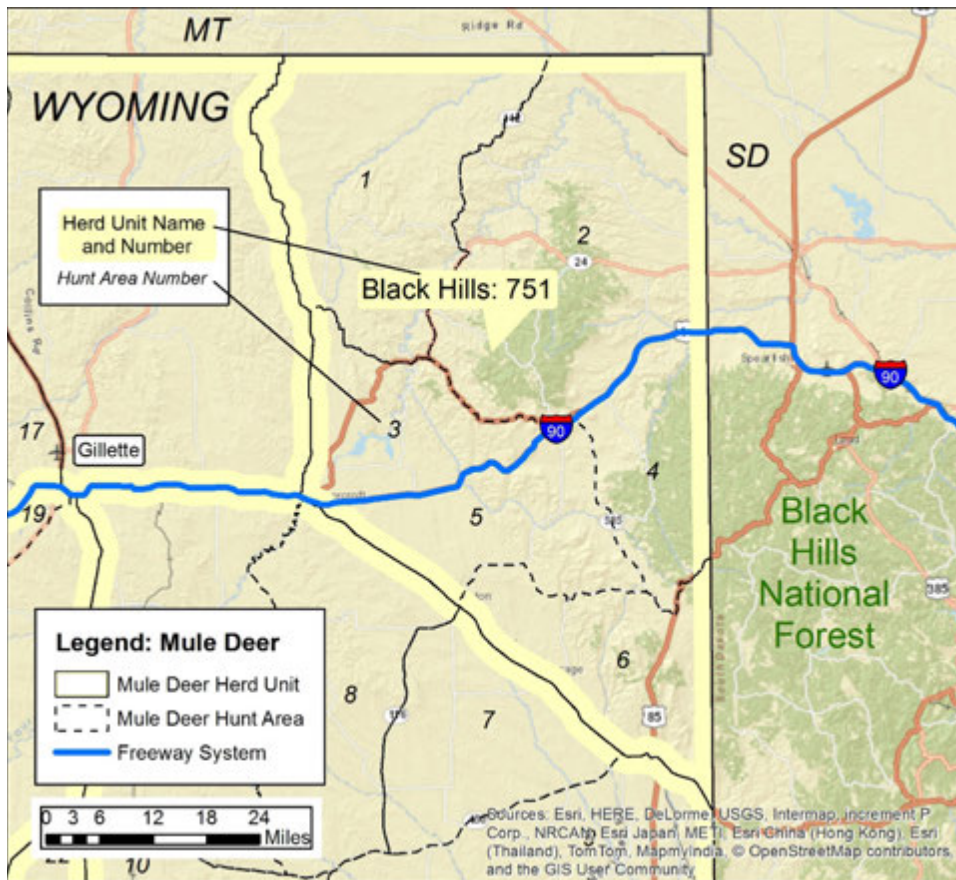


Fig. 89. Wyoming mule deer herd unit 751 (Black Hills)

Land Ownership Land status in the herd unit is a mix of private and public ownership. Private lands account for 77% of the land in the unit, U. S. Forest Service 9%, state lands 7%, Bureau of Land Management 5% and Bankhead/Jones lands 1%. A variety of other government agencies account for another 1% (WGFD 2014).

Land Use Livestock grazing on public and private lands is a major activity in this area. Urban and sub-urban development includes the communities of Newcastle (pop. 3,532), Sundance (1,182) and Moorcraft (1,009) and a number of smaller unincorporated towns and hamlets (TWTER 2014). The area provides ample opportunities for a variety of outdoor recreational activities. During the fall, hunting for small game and big game attracts a number of hunters.

Management Issues The population objective for the Black Hills Mule Herd Unit is an estimated post-season population of 20,000 mule deer, and herd's management strategy is recreational management. It is managed for recreational hunting to limit deer numbers to a level compatible with landowner desires. The population objective and management strategy were set in 1986. Seventy-six percent of the land in this herd unit is privately owned. Significant blocks of accessible public land are found on the Black Hills National Forest in Hunt Area (HA) 2 and HA 4, and on the Thunder Basin National Grassland in HA 6. A block of BLM land with a couple of access points is also present in HA 1. Because the majority of private landowners charge high access fees for hunting, these parcels of public land receive greater hunting pressure than private lands (WGFD 2013).

Historically, management of this herd has been a by-product of managing the Black Hills white-Tailed Deer Herd. Deer hunting seasons have been primarily structured to address the white-

tailed deer population. As with many of the herd units in the eastern half of Wyoming, the Game & Fish Department has tried to maintain deer numbers at levels acceptable to landowners (WGFD 2013).

Population modeling of this herd is very difficult due to movement of animals across herd unit boundaries. The model is considered to be of fair to poor quality due to the lack of herd specific survival data, violations of the closed population assumption, small classification sample sizes some years, and aerial classifications in terrain that makes classifying yearling bucks difficult (WGFD 2013).

Population Size The mule deer population in herd unit 751 has fluctuated substantially over the years. As it is currently presented the minimum population estimate of 12,500 animals occurred in 1980. The maximum population estimate for this herd was 32,431 animals in 2006. The long-term mean value for the population is 20,040 deer. The population estimate for 2012 is 19,505 animals. The long-term trend for the population is increasing. The long-term objective for population size for this herd unit is 20,000 animals. A recent decline in the population occurred between 2006 and 2011 when the population declined from 32,431 animals to 12,973, a decline of 60%.

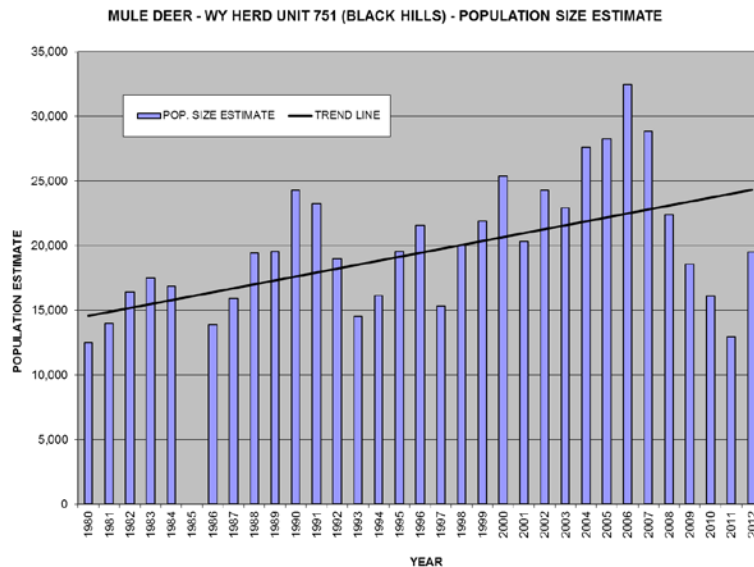


Fig. 90. Mule deer – Wyoming herd unit 751 (Black Hills) – population size estimate

Age and Sex Composition Male/100 female ratios have varied from a low of 10 males/100 females in 1987 to a high of 34 males/100 females in 2000. The mean for all years of data is 20 males/100 females. The overall trend for all years of data shows male/100 female ratios increasing.

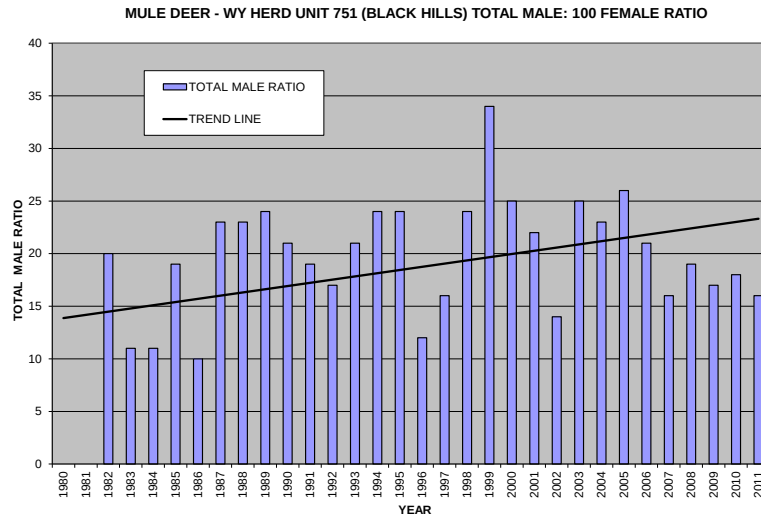


Fig. 91. Mule deer – Wyoming herd unit 751 (Black Hills) – male/100 female ratios

Young/100 female ratios have ranged from a high a high of 99 young/100 females in 1987 to a low of 49 young/100 females in 1997. The mean value for all years of data is 74 young/100 females. The trend for young/100 female ratios is slightly increasing for all years of data.

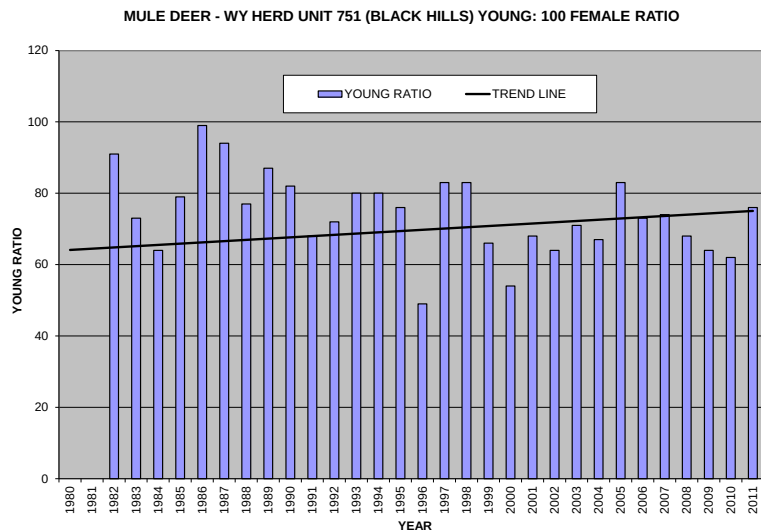


Fig. 92. Mule deer – Wyoming herd unit 751 (Black Hills) – young/100 female ratios

Harvest Total buck harvest for this herd unit has varied from a high 2,756 animals in 1992 to a low of 1,128 animals in 2011. Average buck harvest for this herd unit is 1,917 animals. The long-term trend for buck harvest in the herd unit is declining. A review of buck harvest by decade shows that harvest peaked in the 2000s at an average of 2,090 animals per year but has declined sharply in the 2010s to an average of 1,206 animals per year, value that is only 57% of the average buck harvest for the 2000s.

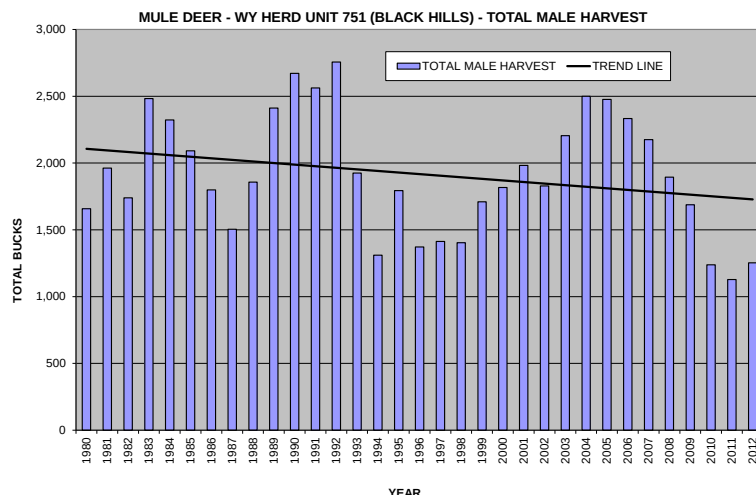


Fig. 93. Mule deer – Wyoming herd unit 751 (Black Hills) – male harvest

Total harvest for the Black Hills herd unit has ranged from a high of 5,792 animals in 1992 to a low of 1,379 animals in 2011. The mean for total harvest for all years of data 2,736 animals. The long-term trend for total deer harvest is slightly decreasing. By far, the period of peak harvest for this herd unit was the early 1990s. Deer harvest has been decreasing in recent years from one of 3 peaks of harvest that have occurred in this herd unit, the latest being in the mid-2000s.

Antlerless deer harvest has occurred in this unit for all years of the analysis. In some years, antlerless harvest made up a substantial portion of total harvest, as much as 52% of the total harvest in the peak harvest year of 1992. However, in most years antlerless harvest comprised 10-30% of the total deer harvest.

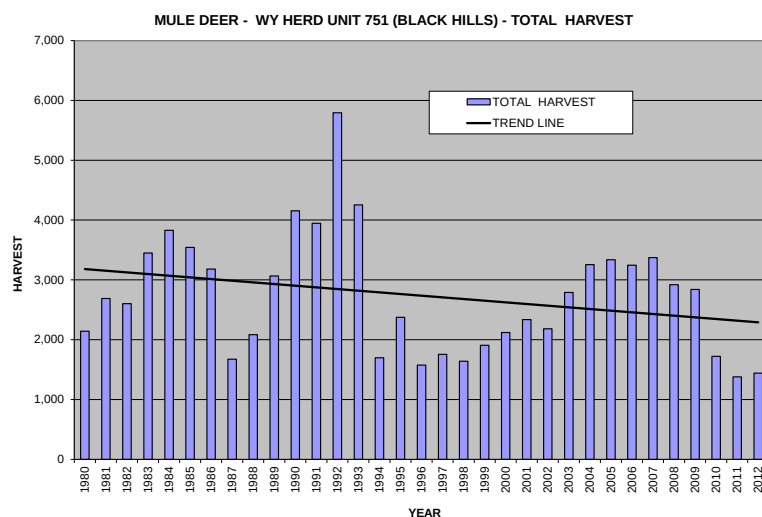


Fig. 94. Mule deer – Wyoming herd unit 751 (Black Hills) – total harvest

Hunter Numbers and Success Rates Total hunting pressure (all seasons and methods of take) has ranged from a high of 13,686 hunters in 1981 to a low of 3,569 hunters in 2012. The mean value for hunter numbers for all years of the analysis is 5,845 hunters. The overall trend for hunter numbers is slightly decreasing. An analysis of hunter numbers by decade shows that this unit supported the most hunters in the 1990s and the fewest number of hunters in the 2010s.

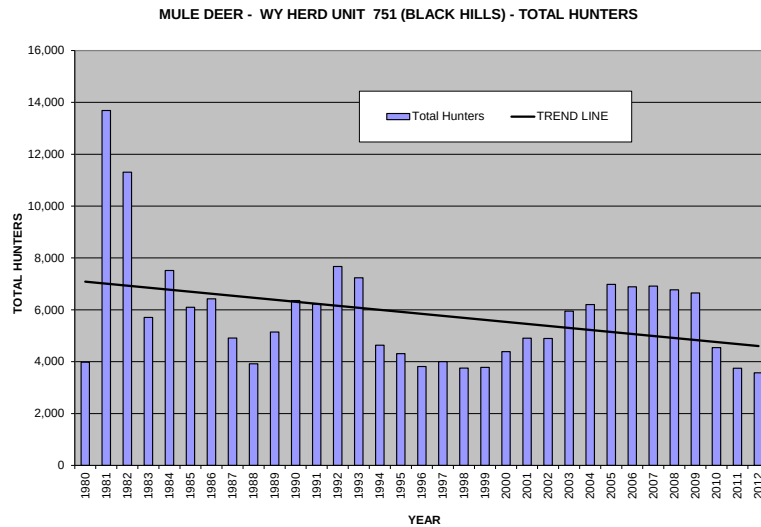


Fig. 95. Mule deer – Wyoming herd unit 751 (Black Hills) – total hunters

Hunter success rates for seasons and methods of take have varied from a low of 20% in 1981 to a high of 76% in 1992. The mean for hunter success for all years of data is 48%. The trend for hunter success for all years of data is level to slightly decreasing. A comparison of hunter success rates by decade shows that the 2010s have the lowest success rate of all decades in the analysis (38%).

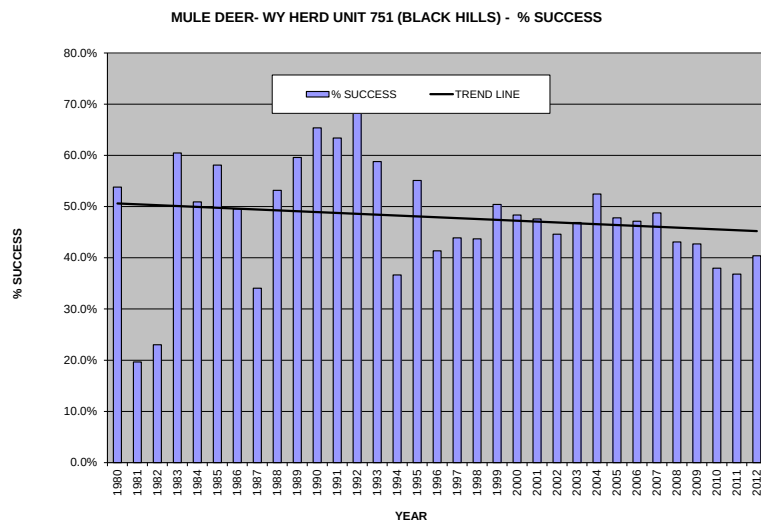


Fig. 96. Mule deer – Wyoming herd unit 751 (Black Hills) – hunter success rates

Summary of Herd Vital Statistics and Management Implications An evaluation of an assortment of data for the mule deer herd in this herd unit indicates that it is performing at nearly an optimum level. According to an evaluation system that was developed for this project, the performance rating for this herd would be good for the following reasons:

- The mule deer population in this herd unit is within 10% of the long term population objective set by the Wyoming Game and Fish Department (19,505 versus 20,000 animals). The last time this herd was at objective was 2008 when the herd was actually above objective at 22,399 animals. This herd has been at objective or within 10% of the object for 8 of the past 10 years.
- The long-term trend for population size for the herd is increasing. However, in the short term (last 5 years) this population has declined from being above long-term objective to

65% of objective and is moving back towards objective again. It is very likely that this herd will reach population objective in a year or two.

- The long-term trend for young/100 female ratios is increasing. Young/100 female ratios for the last 5 years have equaled or exceeded the mean value for young/100 female ratios (74:100) for 2 of 5 years. There is potential for continued herd growth if young/100 female ratios continue at this level.
- The only negative factor for this deer herd is a decreasing long-term trend for harvest. Also, the total harvest of 1,442 animals in 2012 is the second lowest harvest recorded in the 32 year period of this data analysis. In addition, harvest estimates for the last 5 years have been below the long-term mean for harvest (2,736 animals) for 3 of the last 5 years for this herd unit.

The end result of all of this information is that if current habitat conditions are maintained, and if the short-term trend for young/100 female ratios continues, this deer herd will likely continue to show improvement for population size and harvest. However, habitat loss and/or degradation can still have a negative impact on this herd. Impacts to the deer herd would be dependent on the amount and severity of the habitat loss or degradation. Sportsmen and other wildlife enthusiasts should be happy to know that at least one mule deer herd in northeastern Wyoming is performing well in spite of development in surrounding areas.

NORTH CONVERSE, MULE DEER HERD UNIT 755 (refer to appendix, table 11)

General Description Mule deer herd unit 755 is located in eastern Wyoming is referred to as the North Converse Herd Unit. The herd unit lies in portions of Johnson, Campbell, Natrona and Converse counties and contains only hunt area 22. The unit is bounded on the north by State Highway 387, on the east by State Highway 59, on the south by the North Platte River and on the west by Interstate Highway 25 and State Highway 259. The herd unit covers an area of approximately 2,539 square miles with 2,531 square miles of the unit considered to be occupied mule deer habitat. Elevation in the herd unit varies from a high of approximately 6,090 ft. at Blue Hill east of Antelope Hills on Interstate Highway 25 to a low of 4,216 ft. on the North Platte River at Douglas, WY. Topography of the area consist of a rolling upland plain with low to moderate relief, broken by buttes, mesas, hills and ridges (BLM 2003). Vegetation in the herd unit is representative of the Powder River basin sub-region of the northwestern Great Plains eco-region that consists of a mixed-grass prairie dominated by blue gramma, western wheatgrass, junegrass, Sandberg bluegrass, needle-and-thread grass, rabbitbrush, fringed sage, and other forbs, shrubs and grasses (Chapman et al. 2004).