Institute for Policy Integrity
NEW YORK UNIVERSITY SCHOOL OF LAW

April 29, 2016
National Academies of Sciences

Subject: Recommendations for Changes to the Final Phase 1 Report on the Social Cost of Carbon, and Recommendations in Anticipation of the Phase 2 Report on the Social Cost of Carbon

The Institute for Policy Integrity at New York University School of Law[1] respectfully submits these comments to the National Academies of Sciences (NAS) on its review of the social cost of carbon (SCC). Policy Integrity is a non-partisan think tank dedicated to improving government decision-making through scholarship and advocacy in administrative law, economics, and public policy. Policy Integrity and its staff have produced significant scholarship on the social cost of carbon, including running the Cost of Carbon Project.[2]

These comments both recommend changes to the draft Phase 1 report that the NAS should make before finalizing that document, as well as suggest directions for the NAS to take or avoid during Phase 2.

The bulk of the conclusions in the NAS's draft Phase 1 report are appropriate. In particular, the Interagency Working Group (IWG) should not undertake a near-term update of the equilibrium climate sensitivity parameter, but instead should work toward longer-term refinements to its application of the integrated assessment models (IAMs). However, <u>when finalizing the Phase 1 report, the NAS should:</u>

- **Rescind its proposed expansion of the range of SCC estimates** by giving equal weight to low, central, and high estimates at each discount rate, resulting in 9 (or possibly 27) different SCC estimates, including some at or near the improbable value of $0. There is no economic justification for including low percentile estimates; the multiplicity of estimates will confuse agencies, lead to inconsistent cherry-picking of estimates, undermine transparency, and erode public confidence in the SCC methodology; and the inclusion of $0 values raises significant policy and legal difficulties. (See our Recommendation 2.1 below.)
- **Define "consistent" discount rates as "compatible," not "identical," rates.** The NAS's draft proposal for "consistent" discounting is vague, but possibly supports applying different yet theoretically consistent rates. For example, a 3% rate may be appropriate for most short-run benefits and costs in an economic analysis, while a 2.5% or lower rate may be simultaneously appropriate for the SCC, reflecting greater uncertainty. (See Recommendation 3.1.)

<u>In the Phase 2 report, the NAS should:</u>

- **Endorse a focus on the global SCC**, as justified by the economics of international reciprocity and consistent with legal mandates. Focus on a domestic-only SCC would undermine strategic goals and would be misleading, by overlooking significant spillover effects and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders. (See Recommendation 1.)
- **Adopt a certainty-equivalent SCC** as the central estimate for use in decision-making. (See Recommendation 2.2.)
- **Urge the use of declining discount rates**, as consistent with the latest theory and evidence. (See Recommendation 3.2.) The NAS should also call for a normative approach to discounting (see Recommendation 3.4), or minimally for the IWG to include lower constant rates, below 2.5%, to reflect the true range of consumption discount rates (see Recommendation 3.3.).

---

[1] No part of this document purports to present the views, if any, of New York University.
[2] http://www.costofcarbon.org.

- **Expand the module system, first to include a damage function module**, and later to explore adaptation, structural, and tipping point modules. Current IAMs omit significant damage categories, including growth effects; they fail to incorporate the latest economic and scientific data; and they lack direct damage estimates for high temperatures. The IWG should use bottom-up and top-down estimation approaches, including meta-analysis and expert elicitations. (See Recommendations 4.1-4.3.) The NAS should develop criteria for when, if ever, modules should move beyond sensitivity analysis to replace IAM components. (See Recommendation 4.4.)
- **Develop transparent criteria for IAM selection.** There are many more peer-reviewed models besides the three IAMs chosen by the IWG; some models are inter-related, sharing data or structures. The IWG should both expand the range of models it incorporates into its methodology and disclose the relationships between the models chosen. (See Recommendations 5.1-5.2.)
- **Call for the IWG to update its socio-economic assumptions.** (See Recommendations 6.1-6.2.)
- **Call for the federal government to support future research**, including increased funding for a broad set of interdisciplinary researchers. The NAS should highlight key areas for future research, such as monetizing omitted damages and testing climate models' predictive powers. (See Recommendations 7.1-7.2.)

Finally, in adopting any recommendations, the NAS should consider that there is value to maintaining relatively stable SCC estimates over time. Even as the NAS helps guide and push the IWG toward improved estimates based on the best available economics and science, overly frequent—and especially contradictory—fluctuations from one year to the next could create problems. The IWG was convened in 2009 to ensure consistent use of SCC estimates across federal agencies; a degree of consistency over time is likewise valuable. Erratic changes could confuse agencies and erode confidence in the methodology. The NAS should help guide the IWG toward a steady path of constant but careful refinements.

1. A Global SCC Value Is Most Appropriate; a Domestic-Only Calculation Is Misleading

The NAS has received comments signed by a few economists and policy scholars encouraging the NAS to recommend "refocus[ing]" the SCC on domestic impacts, with the global SCC relegated to a "separate reporting" (Fraas et al., 2016). Those comments are misguided on multiple counts. First, they wrongly dismiss the role of strategic motivations in justifying a focus on the global SCC, as well as how the U.S. directly benefits from reciprocal foreign actions. Second, it is a domestic-only, not a global SCC, that is "misleading," because a domestic-only SCC overlooks spillovers and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders. In fact, both methodological limitations and the realities of global economic, atmospheric, ecological, and political systems may make it impossible to accurately calculate a reliable, consistent domestic-only range. Third, they overlook the most recent White House guidance on regulatory policy, which encourages international harmonization. Fourth, they mischaracterize the "current approach" of agencies: in fact, the vast majority of regulatory impact analyses already include both domestic and global calculations, and even the "global" estimates discount foreign welfare to some degree. Finally, these comments are out of the mainstream, with dozens of economists and policy experts supporting a global SCC.

Recommendation 1: The NAS Should Endorse a Focus on the Global SCC, as Justified by the Economics of International Reciprocity, Spillovers, and Willingness to Pay to Prevent Foreign Damages

A. Strategic Motivations, Grounded in Economic Theory, Justify a Global SCC; a Domestic-Only SCC Undermines U.S. Strategic Goals in International Climate Negotiations

Fraas et al. (2016) concede that using the global SCC in U.S. regulatory analysis "might . . . make sense if such actions would help persuade foreign governments that the U.S. had done its part to reduce [greenhouse gas] emissions and therefore other governments ought to do more." Indeed, such strategic motivations are a fundamental justification for a global focus. The United States has specifically chosen a tit-for-tat strategy of harmonizing with other countries on use of the global SCC, and the United States has directly and immensely benefited from foreign actions and commitments on carbon reductions. Highlighting instead a domestic-only SCC would risk undermining long-term U.S. interests in securing reciprocal foreign actions on climate change.

To avoid a global "tragedy of the commons" that could irreparably damage all countries, every nation should set policy according to a global SCC value. "[E]ach pursuing [only its] own best interest . . . in a commons brings ruin to all" (Hardin, 1968). If all countries set their carbon emission levels based on only domestic costs and benefits, ignoring the large global externalities, the aggregate result would be substantially sub-optimal climate protections and significantly increased risks of severe harms to all nations, including the United States. Thus, basic economic principles demonstrate that the United States stands to benefit greatly if all countries apply a global SCC value in their regulatory decisions. In a recent Policy Integrity report, we estimate that foreign climate actions have already directly benefited the United States by upwards of $200 billion, with trillions of dollars more at stake in securing future foreign commitments to reduce more carbon pollution (Howard & Schwartz, 2015).

A rational tactical option in the effort to secure ongoing international cooperation is for the United States to continue using a global SCC value itself. Game theory models have long been applied to climate negotiations (DeCanio & Fremstad, 2013). Under a number of scenarios and assumptions, a strategy of leading by example with unilateral action or continuing a tit-for-tat dynamic could successfully induce ongoing international cooperation on climate change. For instance, in the "coordination" strategic model, all parties realize mutual welfare gains if they all choose mutually consistent strategies. A classic version is when two drivers meet on a narrow road: only when both swerve in the same direction (e.g., both to their right) can they avoid collision. In a coordination model of climate negotiations, unilateral abatement by one major emitting country or bloc of countries can increase the incentive for other governments to also abate. In this strategy, good faith signals can build credibility and trust with other nations, which can increase those countries' perceptions of whether a broadly cooperative outcome is probable, which in turn actually induces cooperation. Trust-building exercises and signals can be especially useful when players are risk adverse (Stewart et al., 2013). Calculating the global costs of U.S. emissions could provide a good faith signal that the United States cares about the welfare of other countries, and finalizing U.S. regulations that use the global SCC value can further increase the incentives for other governments to follow suit.

In a number of additional negotiation structures, a "tit-for-tat" strategy can prove successful in inducing cooperation, once the model reflects more realistic assumptions allowing repeat negotiations over time. For instance, when the "prisoner's dilemma" model assumes that two decision-makers will each have only a single opportunity to choose a strategy, both actors unfortunately perceive that defection is their best personal option, which ultimately leaves both worse off. The classic version involves two criminal co-conspirators being questioned by police in separate rooms, where each end up confessing on the other since their physical separation prevents them from collaboratively making a mutually beneficial agreement to both stay silent. Yet when the model is extended over multiple rounds of decision-making instead, a tit-for-tat strategy allows the actors to punish in future rounds those who fail to cooperate (Wood, 2011). Experiments suggest that tit-for-tat is a very robust strategy in most negotiating environments (Axelrod, 1984). Assumptions that nations will defect or try to free ride in climate negotiations are often based on simple Nash equilibria models that do not capture the real-world conditions that make cooperation more likely. In real negotiations among repeat, sophisticated players, negotiators may have even greater foresight with respect to counter-moves than classic models of strategic behavior may predict. One recent article concludes that, applying more realistic assumptions about foresight with respect to counter-moves, every one of the 25 possible basic game structures that may describe climate negotiations has at least one cooperative solution (Madani, 2013).

Multiple other countries, including the United Kingdom, Sweden, Germany, France, Norway, and Canada, have either adopted a global SCC value or otherwise priced carbon at a global value (Howard & Schwartz, 2016). By matching these global SCC values already in use by other countries, the United States could be seen as continuing a tit-for-tat dynamic designed to reinforce those countries' existing commitments and to encourage reciprocal action from additional countries. In fact, for the United States to now depart from this collaborative dynamic by reverting to a domestic-only SCC estimate could undermine long-term U.S. interests in future climate negotiations and could jeopardize emissions reductions underway in other countries, which are already benefiting the United States by upwards of $200 billion (Howard & Schwartz, 2015). A domestic-only SCC value could be construed as a signal that the United States does not recognize or care about the effects of its policy choices on other countries, and could signal that it would be acceptable for other countries to ignore the harms they cause the United States. Further, a sudden about-face could undermine the United States' credibility in negotiations. If the United States sees the climate negotiations as a repeated dynamic of tit-for-tat, using the global SCC value is a rational strategy.

Universal adoption of the global SCC is not required for use by the United States to be rational. Building a small, stable coalitions of key actors is another viable strategy for securing broader international cooperation over time. Coalitions can lead by example through joint initial commitments to act. Coalitions also foster communication and trust among nations, and they allow member nations to learn by doing and to apply those lessons in future negotiations with other countries (Grasso & Roberts, 2014; Ostrom, 2014; Stewart et al., 2013; Finus, 2008). Some evidence exists that the small coalition strategy is more likely to be successful in climate negotiations if nations' initial commitments are close to their actual optimal emissions reductions and are not mere half-measures (Smead et al., 2014). By joining other nations in using global SCC values and adopting meaningful greenhouse gas limitations, the United States may be employing a coalition-building strategy. Thus, the United States need not hold out for the promise of immediately inducing complete reciprocity among all countries before it is justified in using the global SCC; using the global SCC now can help build a small coalition of key actors, which will both benefit the United States in the short term and help build toward global agreement. (Similarly, after factoring in reasonable predictions on how climate change damages will unfold in the future, even partial reciprocity can justify using a global SCC estimate (Kopp & Mignone, 2013)).

Experiments also show that negotiators balance fairness considerations against pure self-interest. In the classic "ultimatum game" experiment, one player is offered a sum of money to split with another player; only if the second player accepts the split will either get any money. Economic theory would predict that a purely rational first player would offer just one cent to the second player, and a purely rational second player would accept the single penny rather than get nothing. In fact, real first players rarely offer anything less than 30% of the money, and real second players rarely accept any split perceived as unfair. Multiple studies find that, irrespective of the amount at stake in the ultimatum game, first players from industrialized countries typically offer around a 50% split, and second players frequently reject anything less than a 20% share (Sanfey et al., 2003; Oosterbeek et al., 2004). This experimental result "provides evidence that an international environmental agreement is more likely to be stable if it is perceived by its parties to be fair" (Wood, 2011, citing Barrett, 2003). By counting the full global damages of its emissions, the United States may be able to improve its reputation for fairness, building the trust and credibility essential to secure reciprocal actions from other countries.

Quotes from high-ranking officials in the Obama administration suggest that the United States has consciously adopted a tit-for-tat or coalition-building strategy in selecting to emphasize the global SCC value in U.S. regulatory policy. For example, Office of Information and Regulatory Affairs administrator Howard Shelanski (2013) has said "[Climate change] is a global problem, and it seems much easier to exercise global leadership and to get other countries around the world to recognize the social costs of carbon if we are doing so ourselves." Chair of the Council of Economic Advisors Jason Furman has said:

> It is entirely appropriate to include those [global benefits] because we're trying to motivate a range of countries all to act together. . . . If everyone did a social cost of carbon for their own country, everyone would have too low a number and everyone would act too little. And it would make everyone, including the U.S., worse off. . . . [The global SCC is] in effect like a proxy for not only looking at the domestic [benefits], taking into account that we'll get benefits not just from the reduced emissions in the U.S. from our rule, but that it will lead to policy changes . . . from other countries (quoted in Hendrixson, 2014).

The IWG itself explained that a global SCC value was justified in part because "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" (IWG, 2010). And as President Obama (2015) explained in announcing the Clean Power Plan, "[I]f we don't do it, nobody will. The only reason that China is now looking at getting serious about its emissions is because they saw that we were going to do it, too."

Indeed, the U.S. strategy of encouraging international reciprocity through the use of the global SCC is already working. Most recently, Canada—which already based its SCC estimates on the IWG's 2010 global SCC estimates—agreed to continue aligning its SCC with the U.S. SCC in evaluating and setting regulatory policies. As explained by a Joint Statement released by the White House (2016):

> Given the integrated nature of many aspects of the U.S. and Canadian economies, alignment of analytical methods for assessing and communicating the impact of direct and indirect [greenhouse gas] emissions of major projects, and of measures to reduce those emissions, can be mutually beneficial. Canada and the U.S. will align approaches, reflecting the best available science for accounting for the broad costs to society of the GHG emissions that will be avoided by mitigation measures, including using similar values for the social cost of carbon and other [greenhouse gases] for assessing the benefits of regulatory measures.

The United States has good reason to expect additional countries to adopt policies based on the global SCC so long as the United States continues using the global SCC itself; reverting to emphasize a domestic-only SCC would undermine this strategy.

B. A Domestic-Only SCC Would Misleadingly Ignore Spillover Effects and U.S. Willingness to Pay to Prevent Climate Damages Occurring Outside U.S. Borders

Even after conceding that strategic factors can justify the use of a global SCC, Fraas et al. (2016) argue that using the global SCC in U.S. regulatory analysis is "misleading." To the contrary, because a domestic-only SCC ignores spillover effects and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders, a domestic-only SCC would be misleading. Moreover, a domestic-only range may be impossible to calculate accurately.

The United States is not an island. Due to its unique place among countries—both as the largest economy with trade- and investment-dependent links throughout the world, and as a military superpower—the United States is particularly vulnerable to effects that will spill over from other regions of the world. Spillover scenarios could entail a variety of serious costs to the United States as unchecked climate change devastates other countries. Correspondingly, mitigation or adaptation efforts that avoid climate damages to foreign countries will radiate benefits back to the United States as well (Freeman & Guzman, 2009).

As climate change disrupts the economies of other countries, decreased availability of imported inputs, intermediary goods, and consumption goods may cause supply shocks to the U.S. economy. Shocks to the supply of energy, technological, and agricultural goods could be especially damaging. For example, when Thailand—the world's second-largest producer of hard-drives—experienced flooding in 2011, U.S.

consumers faced higher prices for many electronic goods, from computers to cameras (Arthur, 2011). Similarly, the U.S. economy could experience demand shocks as climate-affected countries decrease their demand for U.S. goods. Financial markets may also suffer, as foreign countries become less able to loan money to the United States and as the value of U.S. firms declines with shrinking foreign profits. As seen historically, economic disruptions in one country can cause financial crises that reverberate globally at a breakneck pace (Schwarz, 2008).

The human dimension of climate spillovers includes migration and health effects. Water and food scarcity, flooding or extreme weather events, violent conflicts, economic collapses, and a number of other climate damages could precipitate mass migration to the United States from regions worldwide, perhaps especially from Latin America. For example, a 10% decline in crop yields could trigger the emigration of 2% of the entire Mexican population to other regions, mostly to the United States (Feng, Krueger & Oppenheimer, 2010). Such an influx could strain the U.S. economy and will likely lead to increased U.S. expenditures on migration prevention. Infectious disease could also spill across the U.S. borders, exacerbated by ecological collapses, the breakdown of public infrastructure in poorer nations, declining resources available for prevention, shifting habitats for disease vectors, and mass migration.

Finally, climate change is predicted to exacerbate security threats—and possibly catalyze new security threats—to the United States (CNA, 2014). Besides threats to U.S. military installations and operations abroad from flooding, storms, extreme heat, and wildfires, President Obama (2014) has explained how climate change is "a creeping national security crisis, . . . as [the U.S. military will be] called on to respond to refugee flows and natural disasters, and conflicts over water and food." The Department of Defense's 2014 Defense Review declared that climate effects "are threat multipliers that will aggravate stressors abroad such as poverty, environmental degradation, political instability, and social tensions—conditions that can enable terrorist activity and other forms of violence," and as a result "climate change may increase the frequency, scale, and complexity of future missions, including defense support to civil authorities, while at the same time undermining the capacity of our domestic installations to support training activities" (DOD, 2014). As an example of the climate-security-migration nexus, prolonged drought in Syria likely exacerbated the social and political tensions that erupted into an ongoing civil war, which has triggered an international migration and humanitarian crisis (CAP, 2013; Kelley et al., 2014; Gleick, 2014).

In short, the direct and spillover effects of climate change to the United States are considerable, and carving out any precise, quantified portion of the global SCC that does not apply to the United States is very difficult and controversial. Trying to calculate a domestic-only SCC as either based on geographic boundaries or the U.S. share of global GDP arbitrarily and wrongly assumes that climate damages stop at borders, and ignores the world's deeply interconnected economic, political, and planetary systems. In fact, IAMs currently omit most inter-regional spill overs and socially contingent damages: as a result, calculating any range of domestic SCC estimates is highly inaccurate if not outright impossible.

Additionally, U.S. willingness to pay to prevent climate damages extends beyond strict geographic borders. U.S. citizens have economic and other interests abroad that are not fully reflected in the U.S. share of global GDP. Ownership interests in foreign businesses, properties, and other assets, as well as consumption abroad including tourism and eco-tourism, counsel against a rigid split based on U.S. GDP (EPA, 2008). U.S. citizens have some willingness to pay to protect purely foreign welfare (Rowell, 2015). The United States also has some willingness to pay—as well as perhaps a legal obligation—to protect the global commons of the oceans and Antarctica from climate damages (Madrid Protocol, 1991). Thus, a domestic-only SCC would fail to "provide to the public and to OMB a careful and transparent analysis of the anticipated consequences of economically significant regulatory actions" (OMB, 2011).

C. A Global SCC Is Consistent with the Most Recent White House Guidance and Legal Authorities

Fraas et al. (2016) are wrong that a focus on the global SCC value is inconsistent with Executive Orders and the Office of Management and Budget's guidance for regulatory analysis; in fact, the most recent Executive Order on regulatory policy encourages international harmonization. Fraas et al. focus on two executive orders on regulatory policy and claim that Executive Order 12,866 and 13,563 require an exclusively domestic perspective. Executive Order 12,866 in fact requires agencies to consider "all costs and benefits of available regulatory alternatives" (Clinton, 1993); Executive Order 13,563 expands that, when appropriate, agencies may consider "equity, human dignity, fairness, and distributive concerns" (Obama, 2011). The Office of Management and Budget's guidance on implementing these orders does assume that most regulatory impact analyses would focus on domestic costs and benefits (since most non-climate regulations do have predominantly or exclusively domestic effects), but the guidance ultimately defers to the discretion of individual agencies on whether to evaluate "effects beyond the borders of the United States" (OMB, 2003). To the extent either Executive Order 12,866 or 13,563 implies that agencies should focus on American welfare alone, as explored above, using a global SCC value directly benefits American welfare by stimulating reciprocal foreign actions on climate change that positively affect the United States. But more importantly, these two orders were followed by Executive Order 13609, on "promoting international regulatory cooperation." This 2012 order explicitly recognizes that significant regulations can have "significant international impacts," and it calls on federal agencies to work toward "best practices for international regulatory cooperation with respect to regulatory development" (Obama, 2012). A Regulatory Working Group on Executive Order 13,609 has clarified that cost-benefit analysis ("comparison of costs and benefits") is a "prerequisite[ ] for effective international regulatory cooperation" (RWG, 2015). In fact, the recently announced Canada-U.S. agreement to continue aligning their global SCC estimates represents the very kind of international cooperation envisioned by Executive Order 13,609.

Use of a global SCC value is also consistent with the relevant statutory authorities under which U.S. climate regulations have been promulgated and analyzed. In fact, some legal authorities may require a global perspective. For example, Section 115 of the Clean Air Act requires the control of "international air pollution" (42 U.S.C. § 7415), and the National Environmental Policy Act instructs that "all agencies of the Federal Government *shall* . . . recognize the worldwide and long-range character of environmental problems" (42 U.S.C. § 4332(2)(f)). Similarly, the United Nations Framework Convention on Climate Change (1992) requires that member nations' "policies and measures to deal with climate change should be cost-effective so as to *ensure global benefits* at the lowest possible cost." Policy Integrity's forthcoming report *Think Global: International Reciprocity as Justification for a Global Social Cost of Carbon* (Howard & Schwartz 2016) will further detail such legal requirements. The NAS should generally defer to agencies' interpretations of their statutory authorities, as well as to White House policy on matters touching on international negotiations.

D. The Vast Majority of Regulatory Impact Analyses to Date Discuss Domestic Calculations, though Properly Emphasize the Global SCC, and Even "Global" Estimates Reflect Domestic Biases

Fraas et al. (2016) wrongly state that the "current approach" of regulatory impact analyses is "reporting only the global benefits." In fact, the vast majority of regulatory impact analyses that apply the SCC have included both domestic and global calculations. The Government Accountability Office catalogued all regulatory actions (both proposed and final rules) that used a SCC value through June 2014. Of the 68 regulatory actions catalogued, 42 actions were by the Department of Energy (GAO, 2014), and the Department of Energy has always included domestic calculations in its regulatory impact analyses, even while emphasizing the global value. Most recently, in the agency's March 2016 analysis of its proposed energy efficiency standards for commercial boilers, table 14.4.1 shows "estimates of global present value of CO_2 emissions reductions," and table 14.4.2 shows "estimates of domestic present value of CO_2 emissions reductions" (DOE, 2016). Other agencies, including the Environmental Protection Agency, have also at times included in their regulatory proposals a discussion or calculation of the domestic SCC. For example, EPA's 2011 proposed air quality performance standards for the oil and gas sector first estimated the global value of the rule's climate co-benefits, but also discussed the "provisional and highly speculative" domestic range developed by the IWG (EPA, 2011). Moreover, even when EPA has appropriately chosen to emphasize the global SCC in its rules, the rulemaking dockets still contain EPA's thorough response to any public comments that argue for a domestic-only calculation,[3] as well as copies of the IWG's Technical Support Documents that explain the reason for emphasizing the global SCC and give the provisional range for the domestic-only calculation.[4] Thus, even while agencies routinely provide the public with information on the speculative estimates of the domestic-only SCC, they also correctly emphasize the global SCC value, for the preceding reasons.

Notably, even the "global" calculations of the SCC currently discount foreign welfare to some extent, and thus are arguably already somewhat biased toward a U.S.-centered perspective. Given decreasing marginal utility of consumption and heterogeneity in regional wealth, a dollar loss has heterogeneous welfare effects across regions. Therefore, some modelers have proposed applying equity weights (i.e., weighting the dollar loss in each region by the expect welfare impact it will have in this region) in the calculation of the SCC to accurately measure the change in the "expected value of social welfare" from emissions. Nevertheless, the IWG (2010) rejected equity weighting.[5] Consequently, the IWG's current calculation of the SCC already places relatively greater weight on domestic climate impacts, because it fails to apply equity weights to impacts experienced by foreign countries with lower GDP per capita. Any further weighting or emphasis of domestic impacts would therefore be theoretically and morally questionable.

E. Dozens of Economists and Climate Policy Experts Support the Global SCC

Fraas et al. (2016) are far out of the mainstream with their focus on a domestic-only SCC. The following is a selection of statements from economists and climate policy experts on why a global SCC is the appropriate value:

- "The moral, ethical, and security issues . . . [and the] strategic foreign relations question . . . are compelling reasons to focus on a global SCC" (William Pizer, Matthew Adler, Joseph Aldy, David Anthoff, Maureen Cropper, Kenneth Gillingham, Michael Greenstone, Brian Murray, Richard Newell, Richard Richels, Arden Rowell, Stephanie Waldhoff, Jonathan Wiener, 2014).
- "Another important issue in estimating the SCC was whether to include damages that are projected to occur outside the United States. . . . The interagency group concluded that a global measure of the benefits from reducing US emissions is preferable to a domestic measure because

---

[3] See, e.g., EPA's Response to Comments document for the Clean Power Plan, https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2013-0602-37106, at Section 8.7.2, discussing the 7-23% range and why it was not chosen.

[4] See, e.g., the rulemaking docket for the Clean Power Plan, which includes the 2010 TSD, posted on June 18, 2014, the same day the proposed rule was published for public comments. https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2013-0602-0398.

[5] The IWG (2010) states that "When quantifying the damages associated with a change in emissions, a number of analysts (e.g., Anthoff, et al. 2009a) employ "equity weighting" to aggregate changes in consumption across regions. This weighting takes into account the relative reductions in wealth in different regions of the world. A per-capita loss of $500 in GDP, for instance, is weighted more heavily in a country with a per-capita GDP of $2,000 than in one with a per-capita GDP of $40,000. The main argument for this approach is that a loss of $500 in a poor country causes a greater reduction in utility or welfare than does the same loss in a wealthy nation. Notwithstanding the theoretical claims on behalf of equity weighting, the interagency group concluded that this approach would not be appropriate for estimating a SCC value used in domestic regulatory analysis. For this reason, the group concluded that using the global (rather than domestic) value, without equity weighting, is the appropriate approach."

the climate change issue is highly unusual in at least two respects" (Michael Greenstone, Elizabeth Kopits & Ann Wolverton, 2013).

- "The analysis by the federal Interagency Working Group is significant . . . for its recognition that policy should be based on global, rather than domestic, impacts" (Frank Ackerman & Elizabeth A. Stanton, 2012).
- "Empirical, theoretical, and ethical arguments strongly support the use of a global value" (Laurie Johnson & Chris Hope, 2012).
- "The domestically optimal price approaches the global cooperative optimum linearly with increasing circumspection and reciprocity" (Robert Kopp & Bryan Mignone, 2013).

2. In Recommending a Range of SCC Estimates for Agency Decision-making, More Is Not Always Better

The bulk of conclusions and recommendations in the NAS's first report are appropriate. In particular, the IWG should not undertake a near-term update of the equilibrium climate sensitivity (ECS) parameter or its corresponding distribution to reflect the minor change in the ECS from the 4th to the 5th IPCC reports, given the high opportunity cost of this potential update; instead, the IWG should develop a common climate module to more accurately model warming over the timespan relevant to IAMs. Furthermore, the NAS's call for increased transparency on the uncertainty underlying the IWG's SCC estimates is admirable.

The exception is the NAS's vague fourth recommendation in the draft of its first report. This recommendation jointly addresses the presentation of uncertainty and discount rates. The NAS should clarify and fix the two components of this recommendation in the finalized version of the first report. With respect to the uncertainty, the NAS should rescind its recommendation of the presentation of low and high (e.g., 5th and 95th percentile) SCC estimates conditioned on each discount rate, to avoid the draft recommendation's likely unintended consequences in the application of the SCC in benefit-cost analysis by agencies. If the NAS decides not to make these changes in the finalized version of its first report, the NAS should specify a central SCC estimate for decision making: ideally, a certainty-equivalent SCC.

Recommendation 2.1: In the Final Version of Its First Report, the NAS Should Eliminate Its Current Recommendation that the IWG Include Nine Different SCC Estimates and Should Give Each Equal Weight

The IWG (2010; 2013) recommends four SCC estimates. To calculate these SCC estimates, the IWG (2010; 2013) conducts Monte Carlo simulations of 10,000 random draws for each of the three IAMs (DICE, FUND and PAGE), five socio-economic scenarios (four business as usual scenarios and one mitigation scenario), and three discount rates (2.5%, 3%, and 5%). The resulting output is 45 distributions—one for each IAM, socio-economic scenario, and discount rate combination—made up of 45,000 SCC estimates. By averaging these SCC estimates (applying equal weights) across the various IAMs and scenarios for each discount rate, the IWG produces three final SCC distributions corresponding to each discount rate assumption. Using these distributions, the IWG selects four formal SCC estimates: the mean values of the final SCC distributions for each of the three discount rates, and the 95th percentile of the SCC distribution corresponding to the 3% discount rate. Of these estimates, the mean value of the SCC distribution corresponding to the 3% discount rate is understood as the "central value," and the 95th percentile estimate is understood as a means to address the systematic underestimation of the SCC due to the omission of a risk premium, catastrophic risks, and key negative climate impacts.[6]

[6] The IWG (2015b), in response to comments on the 2013 Technical Support Update, stated the following: (1) "We agree with the commenters who suggested the IAMs do not fully capture the impacts associated with changes

Currently, the NAS draft report (2016) recommends that the Technical Support Document (TSD) "present symmetric high and low values . . . with equal prominence . . . [for] each assumed discount rate." It is unclear if NAS intends just for the TSD to include such values (i.e., present these values for transparency purposes), or if it intends agencies to use those values (i.e., replace the four official SCC estimates currently used by the IWG with these nine estimates). If the former is its intention, the NAS should clarify this intention in the final version of its first report. If the latter is its intention, the NAS should drop this portion of its fourth recommendation given its potential to undermine current objectives of the IWG analysis.

Specifically, the NAS has not justified why 5th percentile estimates would be appropriate or useful, and the NAS has ignored how their introduction undermines the usefulness of the 95th percentile estimate. Currently, the IWG uses the 95th percentile SCC estimate (corresponding to the 3% discount rate) to address the systematic underestimation of the SCC (IWG, 2015b). By requiring equal weighting of the 5th percentile estimates, the NAS is undermining the legitimate role of the 95th percentile, despite the fact that the "IWG is not aware of systematic upward biases in the estimates comparable to the downward biases" (IWG, 2015b). The 95th percentile estimate is intended to account for lower-probability, high-damage, irreversible outcomes as well as risk aversion and other uncertainties and omitted factors. The same kinds of assumptions do not exist to support a 5th percentile estimate: there is no reason to believe the public or the government should be systematically risk seeking with respect to climate change; the consequences of overestimating the risk of climate damages (i.e., spending more than we need to on mitigation) are likely not nearly as irreversible as the consequences of underestimating the risk of climate damages (i.e., catastrophic outcomes); on balance, uncertainties point toward higher, not lower, SCC estimates; and there is no empirical basis for any "long tail" of potential benefits from climate change, unlike the long tail of potential extreme harms. Thus, giving the 5th percentile estimates equal weight as the 95th percentile estimates essentially undermines the current justification of the 95th percentile estimates, and in

---

in climate variability and weather extremes… Similarly, we agree that the models' functional forms may not adequately capture potential discontinuous "tipping point" behavior in Earth system… In fact, large-scale earth system feedback effects (e.g., Arctic sea ice loss, melting permafrost, large scale forest dieback, changing ocean circulation patterns) are not modeled at all in one IAM, and are imperfectly captured in the others. This limitation of the three IAMs is discussed extensively in the 2010 TSD, and again in the 2013 update. The SCC estimate associated with the 95th percentile of the distribution based on the 3 percent discount rate is included in the recommended range partly to address this concern;" (2) "To the extent that [climate catastrophes] may not be adequately represented in the IAMs, the central tendency estimates from these models may not capture the full range of potential damages from CO2 emissions. For this reason, in addition to the three mean SCC estimates using discount rates of 2.5, 3 and 5 percent, the IWG recommended including a rate based on the 95th percentile damage estimate (with a 3 percent discount rate) for the upper end of the range of plausible SCC estimates;" (3) "As the 2010 TSD discusses, the SCC estimates derived from the three integrated assessment models have several significant limitations that could lead to a substantial underestimation of the SCC. These limitations include the incomplete treatment and monetization of non-catastrophic damages, the incomplete treatment of potential catastrophic damages, and uncertainty in extrapolation of damages to high temperatures… The 95th percentile estimate was included in the recommended range for regulatory impact analysis to address these concerns;" (4) "the SCC estimates derived from the three IAMs did not take into consideration the possibility of risk aversion. That is, individuals may have a higher willingness-to-pay to reduce the likelihood of low-probability, high-impact damages than they do to reduce the likelihood of higher-probability, lower-impact damages with the same expected cost. The inclusion of the 95th percentile estimate in the SCC values was also motivated by this concern;" and (5) "the IWG is not aware of systematic upward biases in the estimates comparable to the downward biases discussed above. For this reason, while the IWG has been fully transparent regarding the entire range of uncertainty reflected in the probability distributions, we did not include a 5th percentile estimate in the selected range for regulatory impact analysis… The recommended range represents the central tendency of SCC estimates across three reasonable discount rates, plus a high-end estimate to account for missing damage categories and catastrophic outcomes."

turn would necessitate that the IWG explicitly and separately address risk aversion, catastrophic impacts, and omitted damages.

Assuming that the primary goal of the NAS's fourth recommendation is transparency, requiring the presentation and equal weighting of the 5th percentile SCC estimates may also be counter to this goal. Specifically, the presentation of *nine* SCC estimates in each regulation's benefit-cost analysis may obfuscate analysis conducted by agencies, particularly if insufficient reasoning is provided for the agency's choice of a "central" SCC estimate for decision-making. This is likely to occur if a regulation or proposal is cost-benefit justified under only a subset of (i.e., some, but not all) SCC estimates, and if agencies must use their discretion to determine which set of SCC estimates are valid for decision-making.

For example, a recent proposed rule from the U.S. Forest Service to allow the construction of roads through national forests to enable the operation of new coal mines could not be economically justified under the IWG's four recommended SCC estimates. Therefore, the Forest Service departed from the IWG's recommendations and instead justified its proposal by focusing on a 10th percentile estimate of global SCC values at a 3% discount rate, as well as domestic-only SCC values (Forest Service 2015; Policy Integrity et al., 2016). The fundamental purpose of the IWG's creation in 2009 was to develop a single harmonized range of estimates for all agencies to use, to correct the inconsistent practices up to that time of agencies developing estimates that suited their own goals (GAO, 2014). Should the NAS and the IWG sanction a range of nine SCC estimates, some agencies would see it as license to emphasize for decision-making and public disclosure whichever estimate best fit their objectives. Consistency would erode, and with it the confidence of the public in the SCC estimates overall. Note that these problems would be compounded if coupled with a misguided recommendation to focus equal weight on the domestic and global SCC values. Given that the speculative domestic range itself has a high (e.g., 23% of the global SCC) and low (e.g., 7% of the global SCC) value, the result would be 27 separate estimates (low, central, and high values for each discount rate at the global level, the low domestic level, and the high domestic level). Such an overwhelming number of estimates, with such an enormous range of values, would actually undermine the goal of transparency and create confusion.

Indeed, an overly broad range of SCC estimates could lead agencies and the public to dismiss the entire SCC methodology as meaningless. For example, a Department of Interior field office has cautioned against giving SCC estimates too much consideration because "there is no consensus for the quantitative value of greenhouse gas emissions, and estimates for an incremental ton of carbon dioxide vary widely" (OSMRE, 2015). A sudden expansion to nine (or 27) estimates, including near-$0 estimates at the low end of the 5% rate distribution, would open the entire SCC methodology to challenges. Note also that the U.S. Court of Appeals for the Ninth Circuit (2008) has ruled that "while . . . there is a range of values, the value of carbon emissions reduction is certainly not zero." It is therefore troubling that, in table 5-1 and figure 5-1, the NAS's draft report (2016) suggests that the IWG and agencies should give equal weight to a low estimate of the 5% rate distribution which, at the 10th percentile level, includes $0 estimates.

Though fully transparent presentation of uncertainty is an admirable goal, as the Office of Management and Budget's guidance reminds, "the goal [of regulatory analysis] is not to characterize the full range of *possible* outcomes . . . but rather the range of *plausible* outcomes" (OMB, 2011). The NAS should consider the real world implications, including the likely application of SCC estimates by agencies, before making recommendations.

Recommendation 2.2: The NAS Should Recommend a Central SCC Estimate for Use in Benefit-Cost Analysis by Agencies, and Should Choose the Certainty-Equivalent SCC

If the NAS moves forward with its fourth recommendation as currently drafted, the NAS should recommend in its second report a central (preferably a certainty equivalent) estimate for use in decision-making; this is necessary to address the above problems with the real world application of the SCC in benefit-cost analysis. The certainty-equivalent SCC estimate is the theoretically correct measurement of social costs. Furthermore, given that the introduction of the 5th percentile SCC estimate would undermine the salutary goal served by the 95th percentiles (i.e., the systematic underestimation of the SCC due to the omission of lower-probability, high-damage, irreversible outcomes as well as risk aversion and other uncertainties and omitted factors, as discussed in the previous sub-section), a certainty-equivalent SCC would help address one of these omitted factors: specifically, the omission of a risk premium to account for societal risk aversion. In terms of the criteria that this NAS committee laid out in its first draft report, this recommendation is consistent with the Phase 1 conclusions and recommendations and would significantly change the SCC (NAS, 2016).

The NAS should recommend that the IWG clearly indicate a central estimate for use in the decision criteria of benefit-cost analysis. While providing sensitivity analysis over a range of SCC values can advance transparency goals, if a central estimate is not specified, it can also force regulators—who potentially lack a sophisticated knowledge about the SCC and discount rates—to make a choice of which SCC estimate to use in the decision-making process. This is particularly problematic when a benefit-cost analysis finds that a regulation is justified at some, but not all, of the SCC estimates. By specifying a central SCC for decision-making, the IWG can ensure that the SCC is being uniformly used across all agencies—an essential goal of the IWG (2010).[7] A discussion of the central estimate and how to use it in benefit-cost analysis should be included in the "guidance [section] concerning interpretation of reported SCC estimates for cost-benefit analysis" discussed in the NAS's fourth recommendation.

In a stochastic world, the certainty-equivalent SCC is the ideal central estimate of the SCC (Newbold et al., 2013; Kopp et al., 2012). Under uncertainty, "the 'social cost of carbon' in a particular year is the decrease in aggregate consumption in that year that would change the current *expected value of social welfare* by the same amount as a one unit increase in carbon emissions in that year" (Newbold et al., 2013) (emphasis added). Instead of the unweighted average SCC estimates currently calculated by the IWG (i.e., the expected value), the certainty equivalent SCC is the weighted average of the deterministic SCC where the marginal welfare of consumption is the appropriate weight (Gerlagh, 2014). Thus, only when the marginal utility of consumption is known with certainty (Kopp et al., 2012) does the SCC under uncertainty equal the expected value of the deterministic SCC.[8] Given that this assumption does not hold when the consumption or population path is uncertain—as is assumed by the IWG in its decision to use five socio-economic scenarios—the IWG does not solve for the theoretically correct specification of the SCC.

The certainty equivalent SCC can be calculated (see Kopp et al., 2012). Using the theory developed for discounting the benefits of risky projects (Gollier & Hammitt, 2014), the present value of benefits of a risky project is calculated by determining the certainty-equivalent benefits of the project over time, discounting these benefits using the risk-free discount rate (potentially a declining discount rate), and then summing across time periods. Thus, there is a simple series of steps for calculating the certainty equivalent SCC: (1) calculate change in certainty-equivalent consumption over time due to climate change for the base scenario and the perturbation scenario (e.g., the base emission scenario plus a gigaton of CO_2 emissions in the period of interest), (2) take the difference, and (3) calculate the present value of the change in certainty equivalent consumption (potentially using a declining discount rate). However, to

---

[7] The IWG (2010) states that "The main objective of this process was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures. In this way, key uncertainties and model differences transparently and consistently inform the range of SCC estimates used in the rulemaking process…To ensure consistency in how benefits are evaluated across agencies, the Administration sought to develop a transparent and defensible method, specifically designed for the rulemaking process, to quantify avoided climate change damages from reduced CO2 emissions."

[8] Given the isoelastic utility function commonly assumed by IAMs, the weight is a function of the population, the level of consumption, the pure rate of time preference, and the elasticity of the marginal utility of consumption. However, it is common to assume an exogenous utility function, and great care should be taken if modelers assume that the preference parameters are unknown (Gerlagh, 2014).

make calculations tractable, it is necessary to make the common assumption that the utility function is exogenous such that the pure rate of time preference and the elasticity of marginal utility of consumption are known (Gerlagh, 2014; Newbold et al., 2014).

Using a certainty-equivalence SCC could significantly increase the IWG's current SCC estimates. Using DICE, Kopp et al. (2012) finds a significant difference between the certainty-equivalent SCC and the 50th percentile SCC that increases with relative risk aversion. While the IWG assumes a risk-neutral central planner—thus minimizing this difference—this assumption does not correspond with the literature (i.e., current IAM assumptions) nor with the IWG's own discussion (2010) of the possible values of the elasticity of the marginal utility of consumption. This is an issue that needs to be simultaneously addressed by the NAS. (See our recommendation 3.4 below). However, even with a risk-neutral central planner, the certainty-equivalent SCC does not necessarily collapse to the expected value of the deterministic SCC due to an uncertain population level.[9]

Calculating the certainty equivalent SCC also addresses the IWG's omission of the risk premium corresponding to economic and climate change uncertainty that arises when the central planner is risk averse.

3. The NAS Should Recommend Declining Discount Rates; Otherwise, It Should Recommend an Expansion in the Range of Constant Discount Rates Considered

The fourth recommendation in the interim version of the NAS's first report recommends the use of "consistent" discount rates between the SCC and the benefit-cost analysis in which the SCC is used. Since the NAS did not define "consistency," the NAS should clarify its meaning to avoid confusion by agencies and to ensure the appropriate use of the SCC in benefit-cost analysis. Partially to address this issue and to ensure the choice of discount rates that corresponds with economic theory, the NAS should recommend that the IWG adopt declining discount rates, or at least expand its current choice of discount rates to include a larger range of possibilities.

Recommendation 3.1: The NAS Should Make Clear that "Consistent" Discount Rates With Respect to SCC Estimates and the Benefit-Cost Analysis in Which They Are Applied Does Not Mean Identical Discount Rates, but Instead that the Two Potentially Differing Rates Should Be "Theoretically Consistent"

It is unclear what the NAS means by "consistent" discount rates in the fourth recommendation of its first draft report on the SCC. On the one hand, "consistent" could be interpreted to mean "identical," such that the same discount rate would apply both to the SCC and to all other costs and benefits in the cost-benefit analysis. On the other hand, "consistent" could be interpreted to mean "compatible" and based on the same theoretically-sound methodology (i.e., theoretically consistent): for example, applying a higher discount rate (say 3%) to other costs and benefits may be "consistent" with a lower discount rate (say 2.5%) for the SCC, to account for the greater uncertainty with respect to climate change relative to more short-run benefits and costs. Given that the latter approach is appropriate when climate uncertainty exceeds the short-run uncertainty captured by most benefit-cost analysis in which the SCC is applied, the NAS should clarify in its final Phase 1 report if it intended the second meaning.

---

[9] The weight in state k is $p_k = L_k B C_k^{-\eta}$ where L_k and C_k are the population and consumption per capita in state k, respectively, B is the discount factor, and η is the elasticity of the marginal utility of consumption. Assuming a risk neutral central planner ($\eta = 0$), the weight simplifies to $p_k = L_k B$. Because the certainty-equivalent SCC in period t equals $SCC_t = \left(\sum_k L_{t,k} * B_t * SCC_{t,k}\right) / \left(\sum_k L_{t,k} * B_t\right) = \sum_k L_{t,k} * SCC_{t,k} / \sum_k L_{t,k}$ where $SCC_{t,k}$ is the deterministic SCC in period t and state k, it is easy to see that the certainty-equivalent SCC does not collapse to the expected value of the deterministic SCC if population is uncertain across states, even when the central planner is risk neutral. Instead, it collapses to the population weighted SCC.

Recommendation 3.2: The NAS Should Recommend that the IWG Directly Implement a Declining Discount Rate[10]

To correct for potential problems with real-world applications of the NAS's fourth recommendation in its first report, the NAS should recommend the use of a declining discount rate. In doing so, the NAS will better achieve its stated goal of using the theoretically correct methodologies. Specifically, using one constant discount rate treats inter-generational and intra-generational benefits and costs in the same manner, violating recently developed economic theory (Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014). Adopting a declining discount rate addresses these benefits and costs differently, while ensuring "consistency in decision making" (i.e., applying the same discount rates to benefits and costs in the same time period) (Arrow et al., 2013). Not only are declining discount rates theoretically correct, they are actionable (i.e., doable given our current knowledge), consistent with current IWG assumptions, and solve the practical problems raised by the NAS's fourth draft recommendation as discussed in the above sub-section.

Since the IWG undertook its initial analysis, a consensus (Arrow et al., 2013) has emerged among leading climate economists that a declining discount rate should be used for climate damages to reflect long-term uncertainty in interest rates. This consensus view is held whether economists favor descriptive or prescriptive approaches to discounting (Freeman et al., 2015). Several key papers (Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014) presents arguments that strongly support the use of declining discount rates for long-term benefit-cost analysis in both the normative and positive contexts. Finally, in a recent survey of experts on the economics of climate change, Howard and Sylvan (2015) found that experts support using a declining discount rate relative to a constant discount rate at a ratio of approximately 2 to 1.

Perhaps the best reason to adopt a declining discount rate schedule is the simple fact that there is considerable uncertainty around which interest rate to use: uncertainty in the rate points directly to the need to use a declining rate, as the impact of the uncertainty grows exponentially over time. The uncertainty about future discount rates could stem from a number of reasons particularly salient to climate damages, including uncertainties in future economic growth, consumption, and the interest rate reaped by investments.

In the descriptive setting adopted by the IWG (2010), economists have demonstrated that the expected net present value rule implies a declining certainty equivalent discount rate when (1) discount rates are uncertain, and (2) discount rates are positively correlated (Arrow et al., 2014). Real consumption interest rates are uncertain given that there are no multi-generation assets to reflect long-term discount rates and the real returns to all assets—including government bonds—are risky due to inflation and default risk (Gollier & Hammitt, 2014). Furthermore, recent empirical work analyzing U.S. government bonds demonstrates that they are positively correlated over time; this empirical work has estimated several declining discount rate schedules that the IWG can use (Cropper et al., 2014; Freeman et al., 2014; Arrow et al., 2013).

The current IWG approach (2010; 2013) is internally inconsistent (i.e., the assumptions of constant discount rates and discount rate uncertainty cannot simultaneously hold given the empirical evidence). Applying the descriptive approach, the IWG adopts three constant discount rates, presumably reflecting uncertainty over the true consumption discount rate. While the recent consensus supports the IWG selecting a discount rate based upon declining discount rates, a constant certainty-equivalent discount rate is only appropriate when discount rates are independent and identically distributed (Cropper et al., 2014). Given the above empirical evidence with respect to U.S. government bond yields and the IWG's current uncertainty over the consumption discount rate, this assumption is likely invalid and, according to the

[10] The arguments here are primarily based on: Arrow et al. (2013); Arrow et al. (2014); Cropper et al. (2014); Gollier & Hammitt (2014); and Newell & Pizer (2003).

latest economic theory, the IWG should adopt a declining discount rate schedule. While the IWG (2010) argues for a constant discount rate adjustment based on potential "time inconsistency" when using a declining rate (i.e., that formerly cost-benefit justified policies are no longer justified if the discount rate schedule changes), this can be avoided by regularly updating the discount rate schedule to reflect new information (Arrow et al, 2014). Such updates could be scheduled every two to three years when the IWG meets to update its SCC estimates.

If the IWG were to adopt the normative perspective in the future, economists have demonstrated that an extended Ramsey rule implies a declining discount rate when (1) the growth rate of per capita consumption is stochastic,[11] and (2) consumption shocks are positively correlated over time (or their mean or variances are uncertain) (Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014). While a constant adjustment downwards (known as the precautionary effect[12]) can be theoretically correct when growth rates are independent and identically distributed (Cropper et al., 2014), empirical evidence supports the two above assumptions for the United States, thus implying a declining discount rate (Cropper et al., 2014; Arrow et al., 2014; IPCC, 2014).[13] Several papers have estimated declining discount rate schedules for specific values of the pure rate of time preference and elasticity of marginal utility of consumption (e.g., Arrow et al., 2014), though recent work demonstrates that the precautionary effect increases and discount rates decrease further when catastrophic economic risks (such as the Great Depression and the 2008 housing crisis) are modeled (Gollier & Hammitt, 2014; Arrow et al., 2014). It should be noted that this decline in discount rates due to uncertainty in the global growth path is in addition to that resulting from a declining central growth path over time (Nordhaus, 2014; Marten, 2014).

Another possible declining interest rate schedule for consideration by the IWG is the one proposed by Weitzman (2001).[14] It is derived from a broad survey of top economists in context of climate change, and explicitly incorporates arguments around interest rate uncertainty.[15]

Many leading economists support the United States government adopting a declining discount rate schedule (Arrow et al., 2014; Cropper et al., 2014). Moreover, the United States would not be alone in using a declining discount rate. It is standard practice for the United Kingdom and French governments, among others (Gollier & Hammitt, 2014; Cropper et al., 2014). The U.K. schedule explicitly subtracts out an estimated time preference.[16] France's schedule is roughly similar to the United Kingdom's. Importantly, all of these discount rate schedules yield lower present values than the constant 2.5%

[11] The IWG assumption of five possible socio-economic scenarios implies an uncertain growth path.

[12] The precautionary effect measures aversion to future "wiggles" in consumption (i.e., preference for consumption smoothing) (Traeger, 2014).

[13] Essentially, the precautionary effect increases over time when shocks to the growth rate are positively correlated, implying that future societies require higher returns to face the additional uncertainty (Cropper et al., 2014; Arrow et al., 2014; IPCC, 2014).

[14] Weitzman (2001)'s schedule is as follows:

1-5 years	6-25 years	26-75 years	76-300 years	300+ years
4%	3%	2%	1%	0%

[15] Freeman and Groom (2014) demonstrate that this schedule only holds if the heterogeneous responses to the survey were due to differing ethical interpretations of the corresponding discount rate question.

[16] The U.K. declining discount rate schedule that subtracts out a time preference value is as follows (Lowe, 2008):

0-30 years	31-75 years	76-125 years	126- 200 years	201- 300 years	301+ years
3.00%	2.57%	2.14%	1.71%	1.29%	0.86%

Newell-Pizer rate, suggesting that even the lowest discount rate evaluated by the IWG is too high.[17] The consensus of leading economists is that a declining discount rate schedule should be used, harmonious with the approach of other countries like the United Kingdom. Adopting such a schedule would likely increase the SCC substantially from the administration's central estimate, potentially up to two to three fold (Arrow et al., 2013; Arrow et al., 2014; Freeman et al., 2015).

Recommendation 3.3: If the IWG Decides to Continue Using the Descriptive Approach to Calibrate Constant Discount Rates, the NAS Should Recommend that It Include a Lower Constant Discount Rate than 2.5% to Reflect the True Range of Consumption Discount Rates

The IWG appropriately used consumption discount rates rather than returns on capital. With respect to the discount rate, the IWG conducted sensitivity analysis of the results to three constant consumption discount rates: 2.5%, 3%, and 5%; for each of the discount rates, the TSDs reported the various moments and percentiles of the SCC estimates.

In doing so, the IWG correctly excluded a 7% discount rate, a typical private sector rate of return on capital, for several reasons. First, typical financial decisions, such as how much to save in a bank account or invest in stocks, focus on private decisions and use private rates of return. Private market participants typically have short time horizons. However, in the context of climate change, analysts are concerned with social discount rates because emissions mitigation is a public good, where individual emissions choices affect public well-being broadly. Rather than evaluating an optimal outcome from the narrow perspective of investors alone, economic theory would require that analysts make the optimal choices based on societal preferences (and discount rates). Second, climate change is expected to affect primarily consumption, not traditional capital investments.[18] OMB (2003) guidelines note that in this circumstance, consumption discount rates are appropriate. Furthermore, it corresponds with current IAM modeling structure in which climate change directly affects consumption, and not the return on investment. Third, 7% is considered much too high for reasons of discount rate uncertainty and intergenerational concerns; see our Recommendation 3.2 above. As discussed further below, recent surveys find that the average expert economist (experts on either discounting or climate change) supports a social discount rate of approximately 2% (Drupp et al., 2015; Howard & Sylvan, 2015).

The current range of constant consumption discount rates—2.5% to 5%—may still be too high. According to economic theory, depending on the link between climate risk and economic growth risk, even a rate of 1% may be too high.[19] Furthermore, several expert elicitations on the appropriate discount

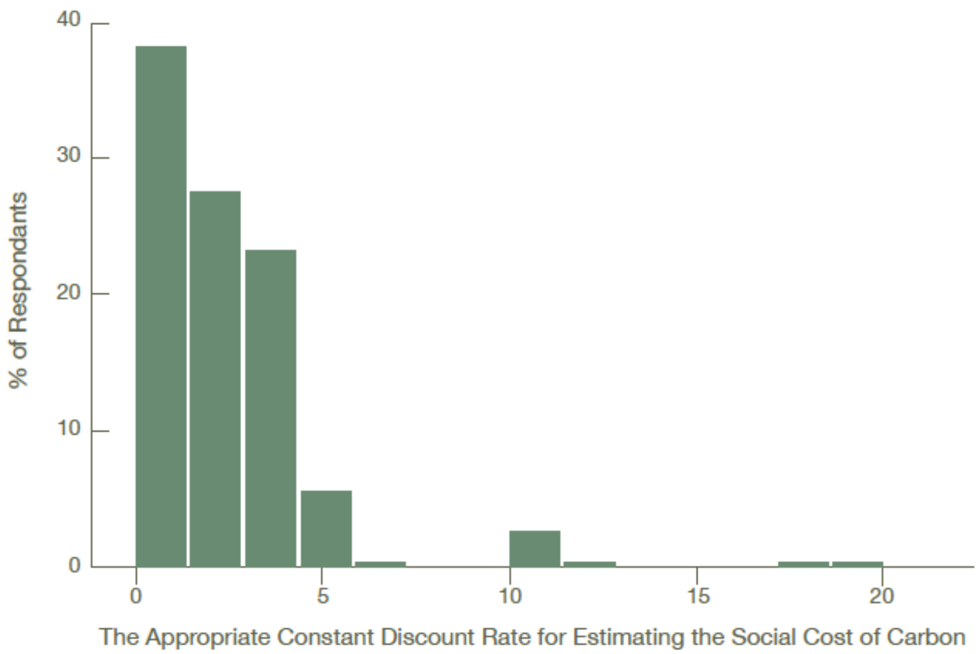
[17] Using the IWG's 2010 SCC model, Johnson and Hope (2012) find that the U.K. and Weitzman schedules yield SCCs of $55 and $175 per ton of CO_2, respectively, compared to $35 at a 2.5% discount rate.

[18] "There are two rationales for discounting future benefits—one based on consumption and the other on investment. The consumption rate of discount reflects the rate at which society is willing to trade consumption in the future for consumption today. Basically, we discount the consumption of future generations because we assume future generations will be wealthier than we are and that the utility people receive from consumption declines as their level of consumption increases. . . .The investment approach says that, as long as the rate of return to investment is positive, we need to invest less than a dollar today to obtain a dollar of benefits in the future. Under the investment approach, the discount rate is the rate of return on investment. If there were no distortions or inefficiencies in markets, the consumption rate of discount would equal the rate of return on investment. There are, however, many reasons why the two may differ. As a result, using a consumption rather than investment approach will often lead to very different discount rates" (Cropper, 2012).

[19] "If climate risk dominates economic growth risk because there are enough potential scenarios with catastrophic damages, then the appropriate discount rate for emissions investments is lower than the risk-free rate and the current price of carbon dioxide emissions should be higher. In those scenarios, the 'beta' of climate risk is a large negative value and emissions mitigation investments provide insurance benefits. If, on the other hand, growth risk is always dominant because catastrophic damages are essentially impossible and minor climate damages are more likely to occur when growth is strong, times are good, and marginal utility is low, then the 'beta' of climate

rate for climate change have found support for discount rates in the IWG's range or lower. Most famously, Weitzman (2001) surveyed 2,160 PhD economists on the appropriate discount rate to use for climate mitigation projects, and found a highly skewed distribution with a mean of 4%, a median of 3%, and a mode of 2%. More recently, Drupp et al. (2015) in a survey of 200 experts (defined as having published on social discounting in a leading economic journal) finds a long-term real social discount rate of approximately 2% (mean and median) with strong support of a range of 1 to 3%. Similarly, Howard and Sylvan (2015) in a survey of over 350 experts[20] (defined as having published on climate change in a leading economics or environmental economic journal) finds a mean and median of 3% and 2%, respectively, as the appropriate constant discount rate for calculating the social cost of carbon (SCC); see Figure 1.[21] Finally, as discussed in the previous sub-section, uncertainty around the correct discount rate pushes the rate lower still (through the precautionary effect), potentially even declining over time (Cropper et al., 2014; IPCC, 2014).

Figure 1. Histogram of responses (with bottom 1% and 99% trimmed) to the question "If benefits to future generations are to be discounted using a constant discount rate, the appropriate discount rate to use when calculating the social cost of carbon is…." (Howard & Sylvan 2015).



risk is positive, the discount rate should be higher than the risk-free rate, and the price of carbon dioxide emissions should be lower" (Litterman, 2013).

In IAMs, the current specification of damages as a percent of GDP implies that climate damages and economic growth are positively correlated, suggesting a higher discount rate than calculated under the Ramsey Rule (IPCC, 2014, Working Group III, 3.6.2). Alternatively, some IAMs implicitly assume that the ability to adapt increases with income, implying a negative correlation and a lower discount rate; see the use of income elasticities in FUND (Anthoff and Tol, 2012; Anthoff and Tol, 2015).

[20] Of the 365 respondents to the survey, approximately 220 answered this open-ended discount rate question.

[21] The higher mean value in Howard and Sylvan (2015) is driven by several extreme outliers, such that "[i]f we trim the full data set to eliminate outliers, the consensus estimate gets even lower. When excluding the 1st percentile and 99th percentile estimates, we find that the mean and median are 2.3% and 2%, respectively" (Howard and Sylvan, 2015). Interestingly, this matches their mean and median responses of experts publishing in economics journals (i.e., excluding environmental journals) without trimming outliers.

The IWG (2010) rejects these lower discount rates based on the "original" Ramsey equation. Specifically, the IWG argues that based on this equation there must be minimum values on the elasticity of the marginal utility of consumption to ensure an appropriate savings rate. Failure to consider a more "realistic" set of assumptions—which lead to more complex Ramsey equations—may partially explain why the IWG (2010) "find[s] it difficult to justify rates at the lower end of [the 1.4 and 3.1 percent] range under the Ramsey framework." Specifically, recent research demonstrates that more realistic preferences than the standard isoelastic utility function—i.e., a CES utility function to capture changing relative prices of non-market and market goods over time and/or an Epstein-Zin utility function to capture observed empirical differences in risk, intra-generational, and inter-generational inequality aversion—and accounting for stochasticity (see our Recommendation 3.2 above) imply extended (and thus more complex) Ramsey discount rate equations. These more realistic discount rate specifications can potentially allow for lower discount rates, while being consistent with current savings behavior (Traeger, 2014; Hoel & Sterner, 2007; Sterner & Persson, 2008; Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014).[22]

Given the new evidence—from surveys, research on preferences, and research on declining discount rates—the NAS should recommend that the IWG consider a wider range of descriptive discount rates, particularly on the lower end of the spectrum.

Recommendation 3.4: The NAS Should Recommend that the IWG Consider Including the Normative Approach to Discounting in Addition to the Positive Approach

There is a split among economists between the normative (i.e., prescriptive) approach and the positive (i.e., descriptive) approach to discounting. In general, the normative approach is appropriate "when [a] new project is financed by an increase in savings from the current generation, so the marginal rate of intertemporal substitution determines the discount rate" (Gollier & Hammitt, 2014). Such is the case in integrated assessment models, which assume a representative agent model that maximizes the present value of utility over multiple centuries (and hence generations). Consequently, the base versions of DICE, FUND, and PAGE use the Ramsey discount rate equation. In addition to theoretical reasons to at least consider using the normative approach, recent surveys found support among relevant groups of experts for the normative approach. In a survey 200 experts on social discounting, Drupp et al. (2015) found that the majority of economists think that both frameworks are relevant, but that the government should place greater weight on the normative approach. Similarly, in a survey of experts on the economics of climate change, Howard and Sylvan (2015) found that experts support calibrating discount rates using ethical norms relative to market rates at a ratio of approximately 2 to 1.

Given the considerable uncertainty in the appropriate normative discount rate (due to uncertainty over the growth path of consumption and differing opinions over ethical parameters such as the pure rate of time preference and the elasticity of the marginal utility of consumption), the IWG should conduct sensitivity analysis over these parameters and variables. There are several options available to the IWG in addition to its current assumptions of a pure rate of time preference of 2.5%, 3% and 5% and an elasticity of marginal utility of consumption of 0 (risk neutral planner) (Kopp et al., 2012). The range of options is laid out on page 21 of the IWG's 2010 Technical Support Document: (1) an elasticity of the marginal utility of consumption between 0.5 to 3, (2) a pure rate of time preference from 0 to 3, and (3) a growth rate of between 1.5% to 2% annually. Given the current assumptions of declining growth rates over time implied by the socio-economic scenarios adopted by the IWG (2010, 2013), these differing assumptions will

[22] For example, introducing an Epstein-Zin utility function tends to imply a discount rate lower than the standard Ramsey formula while potentially solving the equity premium puzzle, though this is somewhat complicated by the correlation between project payoff (i.e., climate damages) and economic growth (Traeger, 2014).

imply a declining discount rate over time when the elasticity of marginal utility of consumption is positive (Nordhaus, 2014; Marten, 2014).

It is necessary for the IWG to consider a more complex Ramsey equation if the normative approach is employed. Recent work demonstrates that the simple Ramsey Rule produces an overly simple view of discount rates, and that the approach should be modified to account for uncertainty (see our Recommendation 3.2 above) and more complex preferences, including relative prices and untangling Arrow-Pratt risk aversion from intertemporal risk aversion (see our Recommendation 3.3 above and Section 8 below) (Drupp et al., 2015; Hoel & Sterner, 2007; Traeger, 2014).

4. An Expansion of the Use of Modules to Climate Damage Functions

In its first report, the NAS suggests (it is not a formal recommendation) that the IWG develop a common climate module to model the relationship between CO_2 emissions and global mean surface temperature over time and the underlying uncertainty in this relationship. According to the NAS, this module should be simple, transparent, and easily updatable, such that the module reflects the best available science with respect to the central tendency and uncertainty in an easy to understand way. The NAS committee further provides specific diagnostic criteria to assess whether the module achieves these goals.

The IWG would benefit from an expansion of this module system to other aspects of IAMs: particularly a damage function module, as well as potentially adaptation, structural, and tipping point modules in the future. Like the climate module, these modules should be simple, transparent, and easy to update, such that they reflect the best available science. Unlike the climate module that is designed to capture central tendency and uncertainty, some of these modules should be designed to primarily reflect the uncertainty currently omitted in current IAMs that systematically bias the SCC (IWG, 2015b). Given the challenge of developing such modules, the IWG would also greatly benefit from explicit directions and/or specific diagnostic criteria.

Given our recommendations in section 2, it is important that including these modules does not result in a further expansion of the number of SCC estimates. Instead, these modules should add to the uncertainty underlying the SCC distributions corresponding to each discount rate. If the NAS recommends a certainty-equivalent SCC (Recommendation 2.2), the additional modular uncertainty would likely increase the IWG's SCC estimate.

Relative to other potential modules (adaptation, structural, and tipping points), it is of great importance to develop a damage function module. This priority is due to the out-of-date nature of current damage functions with respect to the climate damage literature, and the considerable uncertainty underlying damage functions with respect to both calibration and extrapolation (i.e., the choice of the damage function) (Kopp et al., 2012).

As is well known in the literature, the calibration of the current climate damage functions in the IAM literature dates back to the 1990s (Dietz et al., 2007; Revesz et al., 2014). This is true for all three of the models used by the IWG (2013): see Table 1 below for a list of studies used to estimate FUND 3.5; see Table 2 below for calibration sources of DICE-99, upon which DICE-2010 is based; PAGE09 relies on author Chris Hope's discretion to combine various damage estimates, consisting mostly of earlier damage estimates of FUND and DICE (Howard, 2014). Given that many of the economic studies from the 1990s cited by model developers in turn cite scientific literature that predates them, portions of these damage functions may rely on research even greater than two decades old (Revesz et al., 2014). Given that three IPCC assessment reports (2001, 2007, and 2013-2014) have been released since the 1995 report, these damage estimates are likely to omit key information.

There are two general approaches to calibrating climate damage functions: the bottom-up approach (estimating sector and region damage estimates) and the top-down approach (analyzing the total economy using coarser methods) (Mendelsohn et al., 2000). Both of these approaches employ a variety of identification strategies, including enumerative, expert elicitation, meta-analysis, and statistical strategies (Tol, 2009; Howard & Sterner, 2016). For example, with respect to global climate damage estimates, early damage estimates mostly employed the enumerative strategy (e.g., Fankhauser, 1995; Nordhaus & Boyer, 2000) and to a lesser extent surveys (e.g., Nordhaus, 1994) to develop global damage estimates. Second generational damage estimates generally employed cross-sectional estimation techniques (e.g., Rehdanz & Maddison, 2005; Nordhaus, 2008) and continued employing the enumerative strategy (via traditional IAMs and CGE models) (Tol, 2009). Recently, a new generation of statistical studies has used more sophisticated statistical techniques, such as panel methods, to identify climate damages (e.g., Dell et al., 2012; Burke et al., 2015). A similar progression of estimation techniques has been employed at the sector and regional levels, including the latest statistical revolution in regional (e.g., Houser et al., 2014) and sector damages (e.g., for U.S. agriculture, Schlenker & Roberts, 2009). Much of this literature and estimates are currently ignored by DICE, FUND, and PAGE, particularly the most up-to-date damage estimates.

Table 1. Studies Used to Estimate FUND 3.5 Damage Functions

Sector	**Source of Damage Estimate**
Agriculture	Kane et al. (1992), Reilly et al. (1994), Morita et al. (1994), Fischer et al. (1996), and Tsigas et al. (1996)
Forestry	Perez-Garcia et al. (1995) and Sohngen et al. (2001)
Water	Downing et al. (1995) and Downing et al. (1996)
Energy Demand	Downing et al. (1995) and Downing et al. (1996)
Sea-level rise	Hoozemans et al. (1993), Bijlsma et al. (1995), Leatherman and Nicholls (1995), and Nicholls and Leatherman (1995)
Ecosystems	Weitzman (1998; 1992; 1993) and Pearce and Moran (1994)
Health	Martin and Lefebvre (1995), Martens et al. (1995, 1997), Martens (1998), Morita et al. (1995), Link and Tol (2004), and Cline (1992)
Extreme Weather	Toya and Skidmore (2007), WMO (2006), CRED EM-DAT database, and Cline (1992)

Table 2. 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)

There is reason to believe that current IAM damage functions underestimate the magnitude of climate impacts. Contrary to Tol (2009), a forthcoming meta-analysis by Howard and Sterner (2016) finds that climate damage estimates are, if anything, increasing over time (though this result was statistically insignificant). Furthermore, a recent expert elicitation by Howard and Sylvan (2015) of 350 experts on the economics of climate change found that, relative to survey results from Nordhaus (1994), expert consensus estimates increased over the last twenty years on the most likely climate impact (measured as a percentage of GDP loss) and the probability of a catastrophic impacts (defined as a GDP loss of 25% or more) for a 3°C increase (relative to the pre-industrial period) by 2090.[23] These increases in expected impacts over time may partially be driven by the new generation of statistical estimates detailed above (Revesz et al., 2014). Yet given the outdated nature of studies used to calibrate DICE, FUND, and PAGE, including their failure to include this new generation of studies, there is the strong possibility that current IAMs underestimate the magnitude of damages from climate impacts.

In addition to under-estimating the magnitude of current climate damages, IAMs and their corresponding damage functions omit a variety of climate impacts, including impacts on economic growth and input productivity, social conflict, weather variability, ocean acidification, inland flood, and catastrophic impacts (from a variety of sources, such as tipping points) (Howard, 2014; Revesz et al., 2014); some of these omitted impacts are captured by the latest generation of statistical estimates, including conflict (e.g., Hsiang et al., 2011; Hsiang & Burke, 2014), violence (e.g., Cane et al., 2014), and growth (e.g., Dell et al., 2012; Burke et al., 2015; Hsiang & Jina, 2014). But since these impacts are still omitted from current IAMs, the IWG (2015b) has acknowledged that current SCC estimates are systematically biased downwards. In its 2010 and 2013 analyses, the IWG partially addressed these omissions by asking agencies to include the 95th percentile of the SCC distribution corresponding to the 3% discount rate distribution. However, this methodology is potentially eliminated or watered down if the NAS maintains the current wording of its fourth recommendation in the first NAS report (see Section 2 above) and if the IWG adopts this recommendation. Regardless, the IWG may be relying on the 95th percentile estimate to compensate for too many omissions.

The other source of damage uncertainty is due to the relative arbitrariness of damage functional forms (Kopp et al., 2012). Like calibration, this source of uncertainty can also significantly affect the SCC. 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 from low temperature damage estimates to high temperatures; this requires a multitude of assumptions, as in DICE-1999, making damage estimates at high temperature unreliable. Regardless of how analysts select the shape of damage functions, some level of author discretion is currently necessary.[24]

[23] Of the 356 respondents, approximately 230 answered these two open-ended global climate damage questions.

[24] For example, the choice of a quadratic damage function in DICE is more due to historical precedent than empirical validation, whereby Nordhaus (1992;1993) selected this functional form to capture the observation that impacts are increasing at an increasing rate; he cites Cline (1992) based on his finding that damages increase at a power of approximately 1.3 (Nordhaus, 1992). Nordhaus has maintained this assumption throughout the various updates of the DICE model.

Recommendation 4.1: The NAS Should Recommend that the IWG Develop Several Climate Damage Modules that Use Bottom-Up and Top-Down Estimation Approaches to Calibrate Up-To-Date Damage Functions

In addition to estimating each of the IAMs with their base damage function, the IWG should develop climate damage modules to address the problems of outdated and omitted impact estimates. Given the current status of damage functions, substantial updates in the IAMs' damage functions are unlikely to occur by the next iteration of the IWG without substantial funding (Revesz et al., 2014). Furthermore, updating the underlying damage functions has the potential to significantly increase the SCC, given that Nordhaus (2015) finds that different damage functions is the key driver in the difference in SCC estimates between DICE, FUND, and WITCH.

The NAS should recommend that the IWG develop climate damage modules using both the bottom-up and top-down approaches. This multiple-prong approach should be employed for several reasons. First, as demonstrated from the range of past estimates (Tol, 2009; Tol, 2014, Howard & Sterner, 2016), differing estimation strategies may result in substantially different impact estimates, and the subsequent analysis should be robust to the estimation strategy (Howard & Sterner, 2016). Second, as noted by Anthoff and Hope at the NAS's third committee meeting in Washington, D.C. on November 13, 2015, improving damage estimates will likely take decades, and bottom-up and top-down approaches have differing strengths and weaknesses. In particular, bottom-up estimates cannot capture climate impacts that are omitted due to lack of data, which may be partially accounted for in top-down approaches like expert elicitation. Last, the use of multiple methodologies to estimate benefits of a regulation is consistent with previous cost-benefit practices by federal agencies. For example, EPA developed a concentration-response function to estimate mortality caused by particulate matter exposure by using published epidemiological studies (Pope et al., 2002; Laden et al., 2006; Walton, 2009) and EPA's own expert elicitation (Roman et al., 2008; Walton, 2009).[25] Each of the employed methodologies should be transparent and systematic to make them easily updatable.

To develop a bottom-up damage function, the IWG should conduct a systematic review of the empirical regional-sectoral damage literature. Rather than relying on author discretion to combine estimates (a method commonly favored in the enumerative approach), statistical methods including meta-analysis should be used. Examples for the United States include Houser et al. (2014) and EPA (2015), which could potentially be expanded globally. An advantage of this methodology is that it builds up regional-sectoral estimates that can be used to calibrate the different regional-sectoral damage functions of DICE, FUND, and PAGE (by disaggregating empirical estimates to the regional-sectoral breakdowns of each of these models). The disadvantages of this method are that it is time intensive, it can omit key impacts that currently lack empirical estimates, and it may be difficult to extrapolate to developing regions that lack the necessary data.

Currently, the models do not reflect recent research on agricultural changes, which suggest the CO_2 fertilization is overestimated, particularly in the FUND model, and that much, if not all, of the fertilization benefits may be cancelled out by negative impacts on agriculture (e.g., extreme heat, pests, and weeds)

[25] "EPA benefits estimates are the monetized human health co-benefits of reducing cases of morbidity and premature mortality among populations exposed to PM2.5 [fine particulate matter] . . . . The anchor points for these estimates are derived from two empirical (epidemiological) studies of the relationship between ambient PM2.5 and premature mortality (the extended analyses of the Harvard Six Cities study by Laden et al. (2006) and the American Cancer Society cohort by Pope et al. (2002)). Since 2006, EPA had calculated benefits based on these two empirical studies, but derived the range of benefits, including the minimum and maximum results, from an expert elicitation of the relationship between exposure to PM2.5 and premature mortality (Roman et al., 2008). Using alternate relationships between PM2.5 and premature mortality supplied by experts, higher and lower benefits estimates are plausible . . . but most of the expert-based estimates fall between the two epidemiology based estimates (Roman et al., 2008)" (Walton, 2009).

(Ackerman & Stanton, 2013; Schlenker et al., 2005; Fisher et al., 2012). Given the importance of agriculture in previous estimates, special care should be taken to accurately model the effects of temperature, precipitation, weather variability, and CO_2 fertilization on food production (as well as farmer adaptation and trade). If the IWG is not able to adequately model all agricultural impacts it should, at a minimum, conduct a sensitivity analysis whereby it removes CO_2 fertilization benefits.

Two top-down approaches that are easily reproducible and less time intensive are expert elicitation (Nordhaus, 1994; Howard & Sylvan, 2015) and meta-analysis at the global scale (Tol, 2009; Tol, 2014; Newbold & Marten, 2014; Howard & Sterner, 2016). While both method are clearly advantageous from the reproducibility perspective, only surveys allow for the estimation of omitted climate impacts—though only to the extent that they are considered by experts.[26] There is also the potential to derive regional-sectoral estimates, though this has only been done in a general sense up to now for developed versus developing regions and market versus non-market impacts (Nordhaus, 1994). However, in addition to benefiting and suffering from many of the advantages and shortcomings of stated preference, surveys are also dependent on who is defined as an expert: the results differ by academic field, area of expertise, and level of expertise (Nordhaus, 1994; Howard & Sylvan, 2015). To fully capture the level of uncertainty in the climate community, one should ask a broad section of experts, as is done in Nordhaus (1994) and Howard and Sylvan (2015). If instead the IWG is interested in knowing only the view of experts on IAMs, a more objective methodology may be to conduct a meta-analysis of global damage estimates (many of which are authored by these experts).

A meta-analysis of global damage estimates benefits from a rigorous treatment of the literature that is both transparent and reproducible (e.g., Tol, 2009; Tol, 2014; Howard & Sterner, 2016). Any meta-analysis of climate damage estimates—regional, sectoral, or global—by the IWG should meet the standards set by the EPA (2006) and the economic literature (Nelson & Kennedy, 2009; Stanley et al., 2013). At a minimum, this requires accounting for heteroscedasticity, dependence of observations, omitted variable bias, and outliers. Additional care should be taken to address multiple publication bias (Howard & Sterner, 2016). An example of such an analysis is Howard and Sterner (2016). The disadvantages of this methodology are specification error, small samples, and the inability to address omitted impacts in a transparent way. Furthermore, a meta-analysis of global impact estimates does not allow the IWG to break down impacts by region or sector, making this methodology primarily useful for IAMs with one aggregate damage function, like DICE.

Recommendation 4.2: The NAS Should Recommend that the IWG Develop a Damage Module to Explore the Possible Impacts of Climate Change on the Social Cost of Carbon Through Its Effect on Economic Growth.

There is growing empirical evidence that higher temperatures affect labor productivity (Kjellstrom et al., 2009), the growth rate of economic output (Hsiang, 2010; Bansal & Ochoa, 2011;[27] Dell et al., 2012), and the growth rate of exports (Jones & Olken, 2010). Some of these negative effects on growth continue into the medium-run and long-run (Dell et al., 2012; Burke et al., 2015). Most recently, Burke et al. (2015) estimates that temperature and precipitation changes due to climate change could decrease global GDP by 23% by 2100 for a business-as-usual scenario, though this estimate is highly uncertain and is much higher than previous macro-estimates by Dell et al. (2012).[28] Given this evidence, it is not surprising that a recent

[26] Not only does the methodology produce a measure of central tendency that represents the wisdom of the crowd, we can accurately measure subjective probabilities of losses by calibrating probability density functions of damages for each respondent (potentially for a variety of temperature levels) (Howard & Sylvan, 2015).

[27] "Bansal and Ochoa (2011) find that national temperature shocks reduce growth by 0.9 percentage points per °C" (Moyer et al., 2013).

[28] Dell, Jones, and Olken (2012) find a 1.3 percent decline in the economic growth rate of poor countries for a one degree Celsius increase in annual average temperature. However, Burke et al. (2015) is more consistent with previous macro-estimates, and challenges assumptions that climate change will not affect the growth rates of

survey found that 78% of experts on the economics of climate change believe that climate change will affect economic growth (Howard & Sylvan, 2015).

The mechanism through which climate change affects economic growth is still unclear. There are several hypothesized mechanisms in the literature, including input (land, labor, and capital) productivity and stock, social conflict, resources available for adaptation, and returns to investment. See Howard (2014) for a more in-depth discussion.

In their default versions, the popular IAMs (DICE, FUND, and PAGE) all assume the relentless march of output growth (Howard, 2014). Given that current IAMs 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 & Tol, 2005; Tol, 2009; Moyer et al., 2013), it unsurprising that they find that the future is always richer than the present, due to a growth path of per capita consumption that is rarely overwhelmed by climate change. 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., 2014).

Papers that model the potential impact of climate change on economic growth in the context of IAMs consistently find significant effects on the SCC. Several papers have modified DICE to include the potential impacts of climate change on economic growth, and have found significant effects on the SCC or the optimal tax (which equals the SCC on the optimal emissions path) (Dietz & Stern, 2015; Moyer et al., 2014; Moore & Diaz, 2015).[29] 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. Using ENVISAGE, Roson and van der Mensbrugghe (2010) estimate damages of 1.5 percent and 3.5 percent of global GDP for increases of 2.3 degrees Celsius and 4.9 degrees Celsius, respectively, above 2000 temperatures, due to labor productivity alone. Thus, the impact of climate change on economic growth is significant.

The NAS should recommend that the IWG include the potential impact of climate change on economic growth as an additional damage function module. Part of this module would require the IWG to make structural changes to some IAMs included in the analysis (including DICE, FUND, and PAGE), though the exact changes depends on the assumptions made by the IWG about the mechanisms by which climate change affects economic growth (e.g., capital productivity). To develop a specific means of implementation, the IWG could look to papers that have modified DICE and the CGE literature. Care

---

wealthy nations. In particular, Burke et al. (2015) argues that Dell et al. (2012) does not disentangle the impact of climate change on economic growth from the observation that poor nations tend to already be hotter. In other words, it is not clear from Dell et al. (2012) whether developing nations suffer more because they are more dependent on climate-sensitive sectors or because they are exposed to more frequent damaging climate events due to their already high temperatures (Moore & Diaz, 2015). Burke et al. (2015) finds evidence of the latter explanation, implying that developed nations will experience greater losses as they move to higher temperatures, and are not in fact “more” resilient.

[29] Dietz and Stern (2015) find that the optimal price of carbon in 2015 increases by 73% to 168% depending on whether climate damages affect the global capital stock (i.e., 30% of DICE damages allocated to capital loss) or total factor productivity (i.e. 5% of DICE damages allocated to productivity loss), respectively. Moyer et al. (2014) find that much higher SCC estimates are possible if even a small share of climate damages indirectly affects economic output through the level or growth rate of total factor productivity, instead of the level of output directly. Moore and Diaz (2015) find a multi-fold increase in the SCC when they calibrate the damage function of their simplified version of DICE (gro-DICE) to the results of Dell et al. (2012), whereby climate change affects economic growth through total factor productivity declines or capital depreciation; however, they find that this increase depends on whether shifting from developing to developed nation status (i.e., increasing per capita income) makes an economy more resilient to climate change impacts.

should be taken to continue to model non-market and catastrophic damages separately from growth impacts on GDP.

Recommendation 4.3: The NAS Should Recommend that the IWG Develop a Climate Damage Module to Conduct a Sensitivity Analysis to Functional Forms of the Damage Function(s)

Due to the lack of damage estimates for high temperature increases, extrapolation of damages to high temperatures is necessary regardless of the methodology for estimating climate impacts. This is true even for methodologies that can test functional forms, like meta-analysis (e.g., Tol (2014), that still rely on damages corresponding to low temperature to fit their damage functions. Therefore, in addition to conducting a sensitivity analysis with respect to the calibration of damage functions (for low temperature increases), the IWG should conduct sensitivity analysis over the functional form of damage functions using functions common in the literature (see Tol, 2014; Kopp et al., 2012). This additional sensitivity analysis is essential given Kopp et al. (2012)'s finding that functional form shape can greatly affect SCC estimates when the IAM's central planner is risk averse.

Recommendation 4.4: The NAS Should Recommend that the IWG Use Modules (Climate, Damage, etc.) as Additional Sensitivity Analysis Rather than Replacing IAM Components Altogether, or Else Recommend Explicit Selection Criteria for Replacing Components with Modules

Clearly, there is an advantage to sensitivity analysis with respect to modeling components. Specifically, the modules demonstrate the true range of uncertainty in the literature. However, the IWG should not simply replace the IAMs' climate model components with its climate module altogether, nor should it replace IAM damage functions with the damage modules. The point of using three IAMs was to capture the full range of modeling decisions in the literature,[30] and replacing modeling components altogether (i.e., in the base runs instead of in sensitivity analysis runs) would erode this goal.

Another reason for not engaging in the wholesale replacement of particular modeling components of IAMs is that it is unclear where such a process stops. All components in IAMs could be modulized, so it is unclear why the IWG should replace one IAM component and not another. If the NAS does recommend the wholesale replacement of particular IAM components, it should develop criteria for modulization, to answer several key questions: What are the criteria necessary for the modulization of an IAM component? Where does the IWG stop in its modulization of IAMS? At what point would the IWG be better off developing its own IAM?

5. The IWG's Choice of Three IAMs Was Fully Justified, but the Choice of IAMs Should Be Revised Using a Transparently Developed Selection Criteria Developed *A Priori*

In its calculations of the SCC, the IWG relied on the three Integrated Assessment Models (IAMs) available at the time, all with a long record of peer-reviewed publications that link physical and economic effects: the Dynamic Integrated Model of Climate and the Economy (DICE), the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), and Policy Analysis of the Greenhouse Effect (PAGE) (Nordhaus, 2014; Anthoff & Tol, 2012; Hope, 2006). DICE, FUND, and PAGE are well-established, peer-reviewed models, developed over decades of research. They represent the state-of-the-art IAMs. The government's first SCC estimates, published in 2010, used the then-current versions of the models; the recent 2013 update employed revised, peer-reviewed versions of the models but maintained the underlying assumptions of the 2010 IWG analysis.

[30] The IWG (2010) clarifies this intention when it declares that "a key objective of the interagency process was to enable a consistent exploration of the three models while respecting the different approaches to quantifying damages taken by the key modelers in the field."

Recommendation 5.1: The NAS Should Recommend that IWG Consider Expanding the Set of IAMs Used to Calculate the SCC to Include Similarly Peer Reviewed State-of-the-Art IAMs; the NAS Should Provide Model Selection Criteria

Each update of the SCC should also consider including models that, like DICE, FUND, and PAGE, are similarly peer reviewed and based on the state of the art of climate-economic modeling. There are several candidate for inclusion: Climate and Regional Economics of Development (CRED);[31] World Bank's ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model;[32] Fondazione Eni Enrico Mattei (FEEM)'s Intertemporal Computable Equilibrium System (ICES);[33] A Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE);[34] and Fondazione Eni Enrico Mattei (FEEM)'s World Induced Technical Change Hybrid model (WITCH).[35]

To aid in this decision, the NAS should suggest model selection criteria (much like it provided "specific diagnostic criteria" to assess a potential climate module) that should be applied to all models, including currently included models (i.e., DICE, FUND, and PAGE). These criteria should answer a variety of difficult questions. First, and foremost, when is a model sufficiently up-to-date to be used in the IWG analysis? For example, does the model reflect the science and economics laid out in the latest IPCC report? Second, given that models differ in the sets of impacts that they capture, what are the necessary impact categories for a model's inclusion? For example, should ICES and ENVISAGE be omitted because they exclude non-market impacts of climate change? Third, given that many IAMs borrow components from other IAMs and calibrate to similar underlying datasets, when is a model too similar to other IAMs with respect to its structure and/or calibration to be included? For example, should models that are partially calibrated to (i.e., WITCH[36] and PAGE[37]), use similar datasets as (ICES[38] and ENVISAGE[39]), or borrow portions of (i.e., CRED[40]) already included IAMs be treated as independent

---

[31] CRED borrows its fundamental structure from William Nordhaus's DICE and RICE models but also offers significant changes. For one, it uses updated damage functions and Marginal Abatement Cost Curves (MACC). Moreover, it uses different global equity weights, and uses additional state-of-the-art methodologies (Ackerman et al., 2013).

[32] ENVISAGE represents a broader modeling effort by the World Bank, where perhaps the largest contribution is a more detailed sectoral breakdown, using 57 different sectors. This level of analysis allows for a more detailed view of agriculture as well as food and energy sectors that are particularly important to any climate-economy modeling (World Bank, 2014; Roson & Mensbrugghe, 2012). The model captures only market impacts.

[33] ICES is modeling effort by FEEM, and like ENVISAGE is a computer generated equilibrium model with 25 regions and 20 sectors (Eboli et al., 2010; Bosello et al., 2012; FEEM, 2016a). Like ENVSIAGE, the model captures only market impacts.

[34] MERGE is a 9 region integrated assessment model that captures impacts to market and non-market sectors, while explicitly assuming that impacts reach 100% of GDP at 17.7 °C (Manne, 2005).

[35] WITCH—another IAM developed by FEEM—consists of 12 strategically interacting regions within a dynamic economic growth model, which explicitly models the energy section, endogenous technological change, and various mitigation tools. WITCH is unique in that it models endogenous technological change (FEEM, 2106b; Bosetti et al., 2009). The latest version includes an adaptation module (Bosello & Cian, 2014).

[36] According to Bosello and Cian (2014), the latest market damage functions of WITCH are calibrated using versions of DICE (Nordhaus, 2008) and ICES (Bosello et al., 2012).

[37] The market and non-market damage functions of PAGE-2009 are partially calibrated using earlier versions of DICE and FUND (Howard, 2014).

[38] Some ICES damage functions are calibrated using similar datasets as FUND, including agriculture, health, and sea-level rise (Tol, 2002; Bosello et al., 2006; Eboli et al., 2010; Anthoff & Tol, 2013).

[39] Like ICES, ENVISAGE calibrates its health damage function using results from Bosello, Roson and Tol (2006), which uses data from Tol (2002), which provides the basis for calibrating FUND's health impact estimates. Also like ICES, ENVISAGE uses similar data as FUND to estimate impacts from sea level rise (Bosello et al., 2007). Also, ENVISAGE uses similar data to calibrate climate impacts on tourism and energy demand (Eboli et al.,

SCC estimates? Last, how does the potential modularization of IAMs by the IWG affect the selection of models? Given the wide range of potential considerations, it would be helpful for the NAS to lay out its preferred selection criteria in its second report to the IWG to ensure transparency and objectivity. Currently included models should also be re-selected based on these criteria, and dropped if they do not meet these criteria.

Recommendation 5.2: The NAS Should Insist that the IWG Include a Section Discussing How IAMs Are Related

The economic-climate modeling community is small and often relies on a handful of studies to calibrate their models. Many IAM damage functions are at least partially calibrated using similar underlying data, including PAGE (partially based on DICE and FUND), WITCH (partially based on DICE), and ICES and ENVISAGE (partially based on FUND) (Howard, 2014; Eboli et al., 2010; Bosello et al., 2007). Also, many IAMs share similar climate or damage function structures. As a consequence, the various IAMs in the literature are not independent from one another (Hisschemöller et al., 2001). Similar to NAS's recommendation to the IWG to include an explicit section in all future technical supporting documents discussing modeling uncertainty, the NAS should recommend a discussion of how models overlap. If the current "explicit" weighting assumptions are maintained (i.e., equally weighting each IAM and scenario), this overlap is key to understanding the implicit weighting of various assumptions. This discussion becomes ever more important as more climate-economic models are included by the IWG.

6. The IWG Should Update Its Socio-Economic Assumptions

One key input is the use of socio-economic scenarios reflected in the choice of economic growth rates and emissions trajectories. Current IWG socio-economic and emissions scenarios were chosen from the Stanford Energy Modeling Forum exercise (EMF-22) and consist of projections for income/consumption, population, and emissions (CO_2 and non-CO_2). The IWG selected five sets of trajectories, four of which represent business-as-usual (BAU) trajectories (MiniCAM, MESSAGE, IMAGE, and MERGE models) and a fifth that represents a CO_2 emissions pathway with CO_2 concentrations stabilizing at 550 ppm.

Recommendation 6.1: The IWG Should Update Its Socio-Economic Assumptions to Reflect the Latest Shared Socio-Economic Pathways (SSPs)

The assumptions used in calculating the SCC should be updated regularly to reflect the latest thinking around possible scenarios, reflecting the latest Shared Socio-economic Pathways (SSPs) (Ebi et al., 2014). These SSPs should represent the latest, consistent pathways, for example, feeding into the latest IPCC report (e.g., Moss et al., 2008). Ideally, a source of emission pathways, such as the IPCC, would be selected to make it clearer when an update of SSPs is necessary.

Recommendation 6.2: The IWG Should Explicitly Weight the Current Socio-Economic Scenarios Considering the Full Range of Possibilities

By using four BAU trajectories and a fifth declining emissions trajectory, the IWG implicitly places an 80% probability on BAU continuing, a 20% probability on future global commitment to reduce emissions, and a 0% probability on greenhouse gas emissions increasing above BAU. Given the possibility of increases in emissions above those expressed by BAU scenarios, a high-CO_2 emissions pathway should also be considered (or the decision to exclude such a possibility explicitly discussed).

2010; Roson & Mensbrugghe, 2012) using the Hamburg Tourism Model (Hamilton, Maddison & Tol, 2005) and De Cian et al. (2007), respectively.

[40] CRED borrows its fundamental structure from William Nordhaus's DICE and RICE models (Ackerman et al., 2013).

Ideally, the IWG would provide explicit weight for these various scenarios (potentially using expert elicitation), rather than an implicit weighting as currently employed.

7. Future Social Cost of Carbon Research and Funding

The NAS could encourage the IWG, and the federal government more generally, to improve the current research on the SCC.

Recommendation 7.1: The NAS Should Call for Increased Funding of Climate-Economic Research, Distributed to a Broader and Interdisciplinary Community of Researchers

First and foremost, increased funding of climate-economic research is necessary. Currently, funding of economic research on climate change is small relative to the physical sciences (Anthoff, 2013). Given the current lack of funding of climate-economic research, climate-economic modelers do not have the resources to update the structure of their models or the underlying data. This is compounded by publication incentives that do not reward updating models but instead reward developing and testing new theories and questions. This has partially led to integrated assessment models that are outdated (Revesz et al., 2014). Ideally, a funding source would be developed exclusively for climate-economic research, perhaps through the National Science Foundation framework. This funding source should be broad enough to not only fund IAM development and updating, but also improving damage function and other parameter estimation.

Second, the funding of climate-economic research should be distributed to a broader community than just the current IAM community. Currently the IAM community is small: four authors account for the three IAMs used by the IWG (2010; 2013), and only a slightly larger community has worked on climate-economics more broadly. According to David Anthoff, one of the developers of FUND, it is not good for a policy community to be so small; science models of similar importance dwarf IAMs in terms of man hours (Anthoff, 2013). A wider community would provide a greater number of perspectives, while simultaneously increasing the amount of hours spent on these models.

Third, the NAS should recommend that any such funding source should be allocated primarily to interdisciplinary research teams (Revesz et al., 2014). Currently, scientists and economists work independently in the field of climate-economics, with scientists and economists typically citing one another's published work without even communicating. For example, the chain of steps in calibrating the agricultural damage function in an IAM may involve four or more researchers, likely including at least: (1) a scientist who develops a climate scenario, (2) an agronomist and/or economist who uses this scenario to estimate yield and revenue impacts (often regionally), (3) an economist who uses these yield or revenue impacts in a trade model to estimate general equilibrium impacts on regional food consumption, and (4) an integrated assessment modeler who uses these CGE estimates to calibrate their regional-agricultural damage function. This process results in considerable information loss and incompatibility. For example, an estimate of agricultural yield impacts for various crops at the global scale is unusable in IAMs because climate-economists require regional-revenue impacts, which do not currently exist. The NAS should encourage interdisciplinary teams that work from the ground up to develop comprehensive damage estimates for IAMs with each step in mind. This would resemble larger scientific efforts in other fields.

Recommendation 7.2: The NAS Should Highlight Key Areas for Future Research

There are several specific areas of research that the NAS should highlight as needing improvement for the next iterations of the IWG's Technical Support Document. Specifically, research should be focused on improving damage estimation, structural improvements in IAMs, and out-of-sample tests where possible.

A. Future Research on Net Damages

Anthoff and Hope at the NAS's third committee meeting in Washington, D.C. on November 13, 2015 both indicated that improving damage estimates will likely take decades. Thus, bottom-up approaches and top-down approaches to estimating climate damage functions are likely to be necessary estimation strategies for many more decades to come, and both have significant room for improvement. Therefore, considerable investment in the improvement of these approaches to damage estimation is necessary. These approaches should rely on rigorous empirical estimation methods or expert elicitation, rather than relying on author discretion as was common in earlier enumerative studies.

In addition to improving these estimation methods, there are several areas upon which new research should focus.

Key Omitted Impacts: One way that the NAS could greatly improve these damage estimates is to highlight the need for the inclusion of currently omitted climate damages (Howard, 2014). There are several omitted impacts that should be included given their potential to significantly affect the magnitude of damage estimates, including socially contingent impacts (e.g., migration, conflict, and violence), growth effects, and other omitted categories like weather variability, ocean acidification, and wildfires.[41] There are also other impacts that are included in IAMS using only the coarsest of methods (e.g., ecosystems, biodiversity, and tipping points). See Howard (2014) for a complete list of omitted impacts, and an extensive discussion of their relative importance.

In some cases, empirical estimates are available (or increasingly so). However, many of these impacts are omitted for tractability/identification reasons. Specifically, climate change impacts are more likely omitted if they are more difficult to measure scientifically or economically. Thus, impacts that are more scientifically uncertain (e.g., socially contingent impacts and tipping points) and/or more difficult to value (e.g., ecosystem services and biodiversity) are more often omitted, resulting in the inclusion of only relatively certain, market impacts (Yohe & Tirpak, 2007). In general, work is necessary to address these omissions given that they are implicitly valued as zero in the current IAMs used by the IWG.

The NAS should advocate that funds not only be distributed to IAM developers to re-calibrate their models, but to scientists and economists jointly working together to improve the underlying estimation techniques. Until all potentially significant impacts are addressed, the SCC should be understood as a lower-bound estimate (Howard, 2014; Revesz et al., 2014).

Catastrophic Impacts: Catastrophic impacts and climate tipping points (in addition to ecosystem services) are currently only partially captured due to the coarse methodologies employed in their measurement. The IAMs currently model tipping points in differing ways: DICE-2010 explicitly models certainty equivalent damages of catastrophic events as estimated in a survey of experts by Nordhaus (1994); PAGE09 explicitly models a singular, discrete discontinuous event that has a probability of occurring in each time period when the realized temperature is above a specified temperature threshold (beyond which the probability is increasing in temperature); and FUND potentially captures tipping points by modeling the uncertainty of almost 900 parameters (Howard, 2014; Lenton & Ciscar, 2013). Also, several papers have modified these IAMs to explicitly model the effects of particular tipping points, including Nicholls et al. (2008), Link and Tol (2011), and Lemoine and Traeger (2011).

Considerable work is still necessary on this topic, and the NAS could aid the IWG in identifying several research directions (Nordhaus, 2013). First, the NAS should clarify the difference between tipping points,

[41] While the NAS should greatly encourage further research into the impacts of climate change on economic growth (i.e., determining the magnitude of the impact), it is also important to identify the mechanism by which climate change affects economic growth (e.g., capital productivity).

catastrophic impacts, and black swan events[42] (Kopp et al., 2016; Howard, 2014), and require an explicit discussion of these concepts and how they are or are not captured by the IWG. Second, the NAS should suggest that the IWG focus on rapid tipping points that have potential impacts during the time frame of the IAMs (i.e., Gladwellian tipping points),[43] rather than slow tipping points (i.e., tipping elements) (Kopp et al., 2016). Key Gladwellian tipping points include climate system tipping points (Atlantic Meridional Overturning Circulation, Regional North Atlantic convection, West African monsoon, El Niño-Southern Oscillation, Arctic sea ice, coral reefs) and social tipping points (adaptation, migration, conflict) (Kopp et al., 2016). Feedback processes that result in more rapid warming than expected should also be included (Nordhaus, 2013), though this is partially captured by the equilibrium climate sensitivity parameter's probability distributions and the NAS's proposed climate module. Third, work on identifying the appropriate distributions for climate and economic parameters should be conducted following the IWG (2010; 2013) approach for the climate sensitivity parameters. Too often distributions like the triangular distribution (i.e., a probability distribution shaped like a triangle defined by its minimum, maximum, and mode) are chosen (see PAGE and FUND) for reasons of computational simplicity that eliminate the possibility of fat tails (Howard, 2014). Finally, future work is necessary to identify what are catastrophic damages—often measured using expert elicitation (Nordhaus, 2014; Howard & Sylvan, 2015)—and to determine if they overlap with tipping points and fat tails.

Given their potential significance, improved modeling of catastrophic and tipping point impacts should be directly integrated into IAMs. If this does not occur, a module should be developed by the IWG, like the damage and structural modules discussed earlier. Otherwise, climate tipping points, like other omitted impacts, are implicitly valued at zero.

Impacts for High Temperatures: Few damage estimates exist for high temperatures. The vast majority are for a 3°C increase in global average surface temperature relative to the pre-industrial period (i.e., the most likely level of long-run warming from a doubling of CO_2 equivalent emissions) or less (Tol, 2009; Howard & Sterner, 2016).

A very promising direction for future climate damage research—used by Ackerman and Stanton (2012) and Weitzman (2012)—is to assume that climate damages reach 100 percent of GDP when temperatures reach levels inhospitable to humans. Globally, Sherwood and Huber (2010) find that humans cannot live on planet Earth for at least some portion of the year if temperatures increase by 12°C or more. This type of research can also inform regional damage estimates (and migration estimates). Recent work by Pal and Eltahir (2015) find that the Persian Gulf will reach the limits of physical human adaptation to temperature (specifically wet-bulb temperature) by the end of the century under business-as-usual conditions. Identifying when regions become too humid for human life should be a priority of future research, particularly regionally. This will also aid in the estimation of the shape of climate damage functions.

Adaptation: The three IAMs used by the IWG (2010; 2013) 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 & Posner, 2011). Recent empirical evidence finds limited adaptation to climate change in the context of agriculture (Schlenker & Roberts, 2009) and economic growth (Burke et al., 2015).

In the IAMs currently used by the IWG (2013), the modelers account for adaptation in different ways. In DICE, adaptation is implicit in the damage estimates such that adaptation costs are captured in the

[42] Black swan events refer to unknown catastrophic impacts, via unknown tipping point events or parameters with unknown probability distribution functions.

[43] Named after the concept defined by Gladwell, Kopp et al. (2016) define Gladwellian tipping points as "critical thresholds, beyond which realized change keeps pace with committed change." In other words, Gladwellian climate tipping points are climate thresholds beyond which the climate "exhibit[s] rapid shifts between states: specifically, from a state in which" a climate effect "is rare to one in which it is widespread."

underlying estimates used to calibrate their damage functions (Warren et al., 2006). In earlier versions of DICE (DICE-1999, DICE-2007, and DICE-2010),[44] Nordhaus essentially assumed high levels of human adaptation at virtually no cost (IWG, 2010).[45] In FUND, Tol models adaptation explicitly (agriculture, ecosystems, and sea level rise) and implicitly (energy, forestry, human health sectors, water, and storms) in the damage estimates and by allowing regional sector costs to be a function of regional wealth (Anthoff & Tol, 2012); this latter type of adaptation assumes that wealthier societies are better able to adapt to climate change (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. In PAGE09, unlike DICE and FUND, Hope (2011) explicitly models climate adaptation and its costs. 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. If the three IAMS overestimate society's ability to adapt to climate change, 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 & Posner, 2011).

The NAS should encourage climate research on adaptation. First and foremost, the NAS should encourage the IWG to incentivize IAM developers to make their adaptation assumptions explicit, as in PAGE. In the case of DICE, this may be easily done by updating the current versions of AD-DICE (de Bruin et al., 2009) and AD-RICE (de Bruin, 2014), which modify DICE-2007 and RICE-2010, respectively, to explicitly model adaptation. By doing so, the IWG should be able to modify IAM adaptation assumptions or conduct a sensitivity analysis using an adaptation module, similar to the damage module. Second, climate damages are currently only partially a function of the rate of climate change in some IAMs (Anthoff & Tol, 2013, Hope, 2011),[46] and not at all in other IAMs (such as DICE). Given that the rate of climate change is essential in determining the cost and limits of human adaptation, future work is necessary to identify how the rate of climate change affects climate damages through adaptation. This is particularly relevant with the recent U.S. shift towards natural gas, which increases methane emissions relative to CO_2 emissions (methane has a stronger global warming potential than carbon dioxide, but a shorter lifespan). Third, the NAS should argue that some portion of climate-economic funding should be allocated to empirical work on climate adaptation in order to identify the level and limits of such adaptation. This empirical work should not only focus on adaptation, but the potential for maladaptation, potentially barriers to adaptation, and inefficiency. To a great extent, IAMs often assume that adaptation will be perfectly efficient (see FUND's sea level rise adaptation assumptions). Yet adaptation, like output-emissions ratios and backstop technologies, are products of a political-social-economic process for which many barriers exist (Dupris, 2011; Biesbroek et al., 2013).[47] Furthermore, even successful adaptation may raise new risks, such as the increased costs of levee / sea wall failures (e.g., Hurricane Katrina) from building sea walls, or increased social pressures from migration (e.g., the current Syrian migrant crisis observed in Europe).

[44] 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.

[45] According to IWG (2010) and Warren et al., (2006), this is particularly evident for the other market sectors. Though the IWG (2010;2013) modifies the DICE model such that emissions are exogenous, the base version DICE makes strong assumptions about the potential for human mitigation, assuming that 100% mitigation is possible this century and that 120% mitigation is possible in 150 years (Ackerman et al., 2013).

[46] In general, climate damages are not a function of the rate of temperature change. The exception is the agriculture and ecosystem sectors in FUND. However, adaptation will be particularly difficult for faster-than-expected temperature increases (Anthoff & Tol, 2012; Hope, 2011).

[47] Dupuis (2011) states "Barriers to adaptation exist in both the developed and developing world, but they appear to be different. If a lack of material resources might still be the main hindrance to the development and implementation of adaptation measures in less developed countries, in developed countries where the need to act is not as obvious, the political feasibility and acceptance of adaptation policies is of greater relevance."

B. Future Research on Structural Modules

Like damage estimates, structures of many IAMs (i.e., the equations that make up climate-models and how these equations connect) are rigid over their various updates. In particular, the three IAMS used by the IWG are relatively stable since their founding in the 1990s (Revesz et al., 2014). This is despite a rich literature exploring structural assumptions and growing evidence that some assumptions may not hold, particularly in the case of impacts of climate change on growth (addressed above in our Recommendation 4.2), utility functional form, and tipping points (discussed above). Given this literature, the IWG currently understates the potential uncertainty underlying the SCC, often systematically underestimating its impact (IWG, 2015b).

Recently, Gillingham et al. (2015) have argued that parametric uncertainty is a more significant driver of the social of carbon than structural assumptions. This argument is based on analysis of six models, of which three have damage functions (DICE, FUND, and WITCH). Many of these models make similar economic assumptions—e.g., the WITCH damage function (Bosello & Cian, 2014) is calibrated using DICE (Nordhaus, 2008) and ICES (Bosello et al., 2012)—resulting in an under-analysis of potential structural uncertainty as represented by the broader IAM and climate-economic literature. While Gillingham et al. (2015) correctly state that in their subset of models structural uncertainty is less important than parametric uncertainty, it is far too early to dismiss model structure as a key determinant of the SCC. In fact, there is reason to believe that alternative structural assumptions are likely to significantly affect the SCC, particularly with respect to the functional form of the utility function and its implications for the discount rate.

Currently, the IAM literature (particularly DICE, FUND, and PAGE) rely on the "standard intertemporally additive expected utility" function with isoelastic preferences (Traeger, 2014). While simple models are more tractable and sometimes lead to easier to understand, more transparent results, they can also omit key details. For example, current IAMs ignore variable relative prices (Hoel & Sterner, 2007)[48] and heterogeneity in risk aversion (Arrow-Pratt, intertemporal, and ambiguity) (Traeger, 2014). Adopting more complex utility functions potentially results in more realism, but at the cost of calibration (which is not always possible) and more complex discount rate specifications (Hoel & Sterner, 2007; Sterner & Persson, 2008; Traeger, 2014).

With respect to relative prices, climate change is predicted to affect market and non-market goods produced outdoors more than market goods produced indoors; market goods insensitive to climate change account for the majority of GDP (Nordhaus & Boyer, 2000). As a consequence, non-market goods and outdoor-produced goods will become relatively scarcer than indoor-produced goods over time. Based on the law of scarcity, the value of non-market and 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 non-market and outdoor-produced goods and services to indoor-produced goods over time), the developers of the IAMs implicitly assume constant relative prices, and bias the SCC downward. This bias may be significant given that Sterner and Persson (2008)—who replace the isoelastic utility function in DICE with a CES utility function calibrated using reasonable parameter values—find that allowing a change in relative prices can approximately double costs of climate change relative to a model assuming

[48] 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.

constant relative prices (at a 2.5°C increase), though their results are highly dependent on the assumed elasticity of substitution (Neumayer, 1999).[49]

With respect heterogeneity in risk aversion, it is a well-known short coming of current IAMs that their overly simplistic structures imply identical aversion to current risk (Arrow-Pratt relative risk),[50] intra-generational inequality (distributive society within time periods), and inter-generational inequality (distribution society between periods)[51] (Sterner & Persson, 2009; Traeger, 2014; Ackerman et al., 2013b). Empirical work testing this equality find little support for the current equality assumption (Ackerman & Stanton, 2013; Crost & Traeger, 2014). Furthermore, the standard utility assumption implies that society is neutral with respect to inter-temporal risk and ambiguity (i.e., deep uncertainty), though empirical work shows that people are risk averse in these respects, though they are less risk adverse to consumption fluctuations than to risk within a given time period. Beyond the climate change literature, these problems are also well known in the finance literature due to the equity-premium and risk-free rate puzzles (Ackerman & Stanton, 2013; Traeger, 2014; Traeger, 2014b). By introducing one of the solutions to the equity premium puzzle (Epstein Zinn preferences) into DICE, several papers demonstrated that relaxing the current equality assumption significantly increases the SCC.[52]

To capture the true range of uncertainty over the SCC, the NAS should recommend that, at some time in the future, the IWG should develop a structural module, like the climate module and the proposed damage module, that will allow for a sensitivity analysis over various key structural assumptions. This module should allow for more complex utility functional forms, including an explicit model of relative prices and an Epstein-Zin utility function. The NAS should qualify this recommendation given the need for additional empirical work to: (1) identify the elasticities of substitution between indoor-produced market goods, outdoor-produced market goods, and non-market goods, (2) estimate the aversion to risk, intra-generational inequality, and inter-generational inequality, and (3) improve the computational methods (for purposes of tractability). Before requiring the development of a structural module, empirical issues such as these should be resolved to some satisfactorily level, given their significant effect on the resulting SCC estimates (Neumayer, 1999; Ackerman et al., 2013b).

As a side note, relative prices have implications for the portion of the NAS's charge about the relative advantages of aggregate and disaggregate damage functions (Gillingham, 2015). While relative prices do not imply that the IWG should use one or the other of these approaches, the specification of disaggregate damages functions (such as in FUND or PAGE) [53] not only facilities the modeling of relative prices, but

[49] The lower the actual elasticity of substitution is (i.e., 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.

[50] This is the risk that society experiences within a time period, such as the flip of a coin. In other words, this is the risk aversion that humans experience to gambling (Crost & Traeger, 2014).

[51] This measures humans' desire for smooth consumption over time (Crost & Traeger, 2014), which is why it is also known as the intertemporal elasticity of substitution (Ackerman et al., 2013b).

[52] Using DICE, Ackerman et al. (2013b) calibrate an Epstein-Zin utility function for 5 possible future states of the climate sensitivity parameter (where uncertainty resolves by 2075), and find a four-fold increase in the SCC. Crost and Traeger (2014) find a more than doubling of the optimal tax (the SCC on the optimal emissions path) from the use of the Epstein-Zin utility function in the context of uncertainty over the damage function. Jensen and Traeger (2014) find an increase in the optimal tax in the context of uncertainty growth.

[53] While FUND and PAGE specify multiple damage functions, DICE specifies an aggregate damage function. However, in some cases, this damage function can be interpreted as the aggregation of multiple damage functions. On the one hand, Nordhaus calibrated the DICE-2007 and DICE-2010 damage functions using the enumerative approach, such that sector-regional (or just sector) damage functions can be disaggregated if all damage functions are assumed to be quadratic. On other hand, Nordhaus calibrated the DICE-2013 damage function using the meta-analysis approach, making such a disaggregation impossible.

almost necessitates the modeling of relative prices by maximizing the value of this approach. Specifically, if the NAS recommends specifying a disaggregate damage function and the perfect substitutability assumption, it would be advocating for throwing out valuable information.

C. Future Research on Testing Climate Models

Considerable work is necessary to test climate-economic models' predictive powers. Ideally economic models would conduct back-casting or out-of-sample prediction, as in the science literature. However, this is difficult to do given that, unlike climate science variables such as sea-level rise and temperatures, long-run time series data on climate damage is unavailable and because of the long time horizon relevant for climate change. Given the difficulty of conducting the types of tests employed in the science literature, the NAS should recommend other means by which to test IAMs.

First and foremost, statistical work is necessary to empirically test whether current structural assumptions hold in the past. For example, empirical work is necessary to identify the mechanism by which climate change affects economic growth. In doing so, modelers will be able to integrate the impacts of climate change on economic growth in a realistic manner to improve their predictive capacity. Additionally, analysts should test whether more complex preferences are necessary by: (1) testing the equality of societal aversion to intergenerational and intergenerational risks and inequality, and (2) testing whether the elasticity of substitution between market goods and non-market goods is infinite. If these equalities do not hold, more empirical work is necessary to estimate these parameter values to integrate them into IAMs through Epstein-Zin preferences and relative prices, respectively.

Second, the NAS should recommend that IAMs test their models against real-world scientific results. For example, the NAS recommended that the IWG develop a climate module to match the current consensus on climate impacts. Similarly, the NAS could recommend that IAMs replicate when particular regions and the Earth will become inhospitable, following the work of Sherwood and Huber (2010) and Pal and Eltahir (2015). This would ensure that climate damage functions are consistent in some way with physical science predictions.

Sincerely,

Peter Howard, PhD, Economics Director

Jason A. Schwartz, Legal Director

Institute for Policy Integrity

References

Ackerman, F. & Stanton, E.A. (2012). Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. *Economics e-Journal*, *6*, 1.

Ackerman, F. & Stanton, E.A. (2013). CLIMATE ECONOMICS: THE STATE OF THE ART.

Ackerman, F., Stanton, E.A., & Bueno, R. (2013). CRED: A new model of climate and development. *Ecological Economics*, *85*, 166-176.

Ackerman, F., Stanton, E.A., & Bueno, R. (2013b). Epstein–Zin Utility in DICE: Is Risk Aversion Irrelevant to Climate Policy?. *Environmental and Resource Economics*, *56*(1), 73-84.

Anthoff, D., & Tol, R.S. (2010). THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, version 3.5.

Anthoff, D., & Tol, R.S. (2012). THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, version 3.6.

Anthoff, D., & Tol, R. S. (2014). THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, version 3.9.

Anthoff. D. (2013). Talk at the Cost-Benefit Analysis and Issue Advocacy Workshop: Policy Integrity's Fifth Anniversary and Twentieth Anniversary of Executive Order 12,866. New York University School of Law. Available at http://www.law.nyu.edu/news/IPI-Workshop-2013.

Arrow, K.J., Cropper, M.L., Gollier, C., Groom, B., Heal, G.M/, Newell, R.G., ... & Sterner, T. (2013). Determining benefits and costs for future generations. *Science*, *341*(6144), 349-350.

Arrow, K.J., Cropper, M. L., Gollier, C., Groom, B., Heal, G.M., Newell, R.G., ... & Sterner, T. (2014). Should governments use a declining discount rate in project analysis? *Review of Environmental Economics and Policy*, reu008.

Arthur, C. (2011). Thailand's Devastating Floods Are Hitting PC Hard Drive Supplies. *The Guardian*, Oct. 25.

Axelrod, R. (1984). THE EVOLUTION OF COOPERATION.

Bansal, R., & Ochoa, M. (2012). Temperature, aggregate risk, and expected returns. *Unpublished working paper, Duke University*.

Barnett, J., & O'Neill, S. (2010). Maladaptation. *Global Environmental Change*, *20*(2), 211-213.

Barrett, S. (2003). ENVIRONMENT AND STATECRAFT.

Biesbroek, G.R., Klostermann, J.E., Termeer, C.J., & Kabat, P. (2013). On the nature of barriers to climate change adaptation. *Regional Environmental Change*, *13*(5), 1119-1129.

Bosello, F., & Cian, E.D. (2014). Documentation on the development of damage functions and adaptation in the WITCH model. *CMCC Research Paper*, (RP0228).

Bosello, F., Eboli, F., & Pierfederici, R. (2012). *Assessing the economic impacts of climate change: An updated CGE point of view* (No. 02.2012). Nota di lavoro, Fondazione Eni Enrico Mattei: Climate Change and Sustainable Development.

Bosello, F., Roson, R., & Tol, R.S. (2006). Economy-wide estimates of the implications of climate change: Human health. *Ecological Economics*, *58*(3), 579-591.

Bosello, F., Roson, R., & Tol, R.S. (2007). Economy-wide estimates of the implications of climate change: Sea level rise. *Environmental and Resource Economics*, *37*(3), 549-571.

Bosetti, V., Tavoni, M., De Cian, E., & Sgobbi, A. (2009). *The 2008 WITCH model: new model features and baseline* (No. 85.2009). Nota di lavoro//Fondazione Eni Enrico Mattei: Sustainable development.

Burke, M., Hsiang, S.M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*.

Burtraw, D. & Sterner, T. (2009). Climate Change Abatement: Not "Stern" Enough? *Resources for the Future Policy Commentary Series*.

Cane, M.A., Miguel, E., Burke, M., Hsiang, S.M., Lobell, D.B., Meng, K.C., & Satyanath, S. (2014). Temperature and violence. *Nature Climate Change*, *4*(4), 234-235.

[CAP] Center for American Progress. (2013). THE ARAB SPRING AND CLIMATE CHANGE: A CLIMATE AND SECURITY CORRELATIONS SERIES.

Cline, W.R. (1992). THE ECONOMICS OF GLOBAL WARMING. *Peterson Institute Press: All Books*.

Clinton, W.J. (1993). Executive Order 12,866: Regulatory Planning and Review. *Federal Register, 78*, Sept. 30.

CNA Military Advisory Board (2014). National Security and the Accelerating Risks of Climate Change.

Cropper, M.L. (2012). How Should Benefits and Costs Be Discounted in an Intergenerational Context?. *Resources for the Future Discussion Paper*, (12-42).

Cropper, M.L., Freeman, M.C., Groom, B., & Pizer, W.A. (2014). Declining discount rates. *The American Economic Review 104*(5), 538-543.

Crost, B., & Traeger, C.P. (2014). Optimal CO2 mitigation under damage risk valuation. *Nature Climate Change*, *4*(7), 631-636.

De Bruin, K.C., Dellink, R.B., & Tol, R.S. (2009). AD-DICE: an implementation of adaptation in the DICE model. *Climatic Change*, *95*(1-2), 63-81.

De Bruin, K.C. (2014). Calibration of the AD-RICE 2012 model. CERE Working Paper, 2014:3.

DeCanio, S.J. & Fremstad, A. (2013). Game Theory and Climate Diplomacy. *Ecological Economics*, 85, 177.

De Cian, E., Lanzi, E., & Roson, R. (2007). *The impact of temperature change on energy demand: a dynamic panel analysis* (No. 2007.46). Fondazione Eni Enrico Mattei.

Dell, M., Jones, B.F., & Olken, B.A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 66-95.

Dietz, S., Hope, C., Stern, N., & Zenghelis, D. (2007). Reflections on the Stern Review (1) A Robust Case for Strong Action to Reduce the Risks of Climate Change. *World Economics*, *8*(1), 121-168.

Dietz, S., & Stern, N. (2015). Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions. *The Economic Journal*, *125*(583), 574-620.

[DOD] U.S. Department of Defense. (2014). Quadrennial Defense Review.

[DOE] U.S. Department of Energy. (2016). Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment—Commercial Packaged Boilers.

Drupp, M.A., Freeman, M., Groom, B., & Nesje, F. (2015). Discounting disentangled: an expert survey on the determinants of the long-term social discount rate. *Available at SSRN 2616220*.

Dupuis, J. (2011). Political Barriers to Climate Change Adaptation. United Nations' *Our World*. Available at http://ourworld.unu.edu/en/political-barriers-to-climate-change-adaptation.

Ebi, K.L., Hallegatte, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J., ... & Winkler, H. (2014). A new scenario framework for climate change research: background, process, and future directions. *Climatic Change*,*122*(3), 363-372.

Eboli, F., Parrado, R., & Roson, R. (2010). Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics*, *15*(05), 515-533.

[EPA] U.S. Environmental Protection Agency. (2006). Report of the EPA Working Group on VSL Meta-analysis. Available at http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0494-01.pdf/$file/EE-0494-01.pdf

[EPA] U.S. Environmental Protection Agency. (2008). Advanced Notice of Proposed Rulemaking: Regulating Greenhouse Gas Emissions Under the Clean Air Act. *Federal Register, 73*, 44,354.

[EPA] U.S. Environmental Protection Agency. (2011). Proposed Rulemaking: Oil and Natural Gas Sector—New Source Performance Standards and National Emissions Standards for Hazardous Air Pollutants Reviews. *Federal Register, 76*, 52,738.

[EPA] U.S. Environmental Protection Agency. (2015). Climate Change in the United States: Benefits of Global Action. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

Fankhauser, S. (1995). VALUING CLIMATE CHANGE: THE ECONOMICS OF THE GREENHOUSE. Routledge.

Fankhauser, S., & Tol, R.S.J. (2005). On climate change and economic growth. Resource and Energy Economics, 27(1), 1-17

FEEM. (2016a). ICES, http://www.feem.it/getpage.aspx?id=138&sez=research&padre=18&sub=75&idsub=102 (last visited March 15, 2016).

FEEM. (2016b). WiTCH, http://www.witchmodel.org/, (last visited March 15, 2016).

Feng, S., Krueger, A.B., & Oppenheimer, M. (2010). Linkages Among Climate Change, Crop Yields and Mexico-U.S. Cross-Border Migration. *Proceedings of the National Academies of Sciences*, *107*, 14,257.

Finus, M. (2008). Game Theoretic Research on the Design of International Environmental Agreements: Insights, Critical Remarks, and Future Challenges. *International Review of Environmental and Resource Economics*, *2*, 29.

Fisher, A.C., Hanemann, W.M., Roberts, M.J., & Schlenker, W. (2012). The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather: comment. *The American Economic Review*, *102*(7), 3749-3760.

[Forest Service] U.S. Forest Service, U.S. Department of Agriculture. (2015). Supplemental Draft Environmental Impact Statement: Colorado Roadless Rule.

Fraas, A., Lutter, R., Dudley, S., Gayer, T., Graham, J., Shogren, J.F., Viscusi, W.K. (2016). Letter to the National Academies of Sciences, "Should the Federal Regulatory Agencies Report Benefits to Americans from Mandated Reductions in Greenhouse Gas Emissions."

Freeman, J. & Guzman, A. (2009). Climate Change and U.S. Interests. *Columbia Law Review*, *109*, 1531.

Freeman, M.C., Groom, B., Panopoulou, E., & Pantelidis, T. (2015). Declining discount rates and the Fisher Effect: Inflated past, discounted future? *Journal of Environmental Economics and Management*, *73*, 32-49.

Freeman, M.C., & Groom, B. (2015). Positively gamma discounting: combining the opinions of experts on the social discount rate. *The Economic Journal*, *125*(585), 1015-1024.

[GAO] Government Accountability Office. (2014). Development of Social Cost of Carbon Estimates. GAO-14-663.

Gerlagh, R. (2014). Calculating the Social Costs of Carbon Without Knowing Preferences: Comment On "A Rapid Assessment Model For Understanding The Social Cost Of Carbon." *Climate Change Economics*, *5*(02), 1450004.

Gillingham, K. (2015). Committee on Assessing Approaches to Updating the Social Cost of Carbon: Sponsors' Interests and Goals for the Study. Available at http://sites.nationalacademies.org/cs/groups/dbassesite/documents/webpage/dbasse_169499.pdf.

Gillingham, K., Nordhaus, W.D., Anthoff, D., Blanford, G., Bosetti, V., Christensen, P., ... & Sztorc, P. (2015). *Modeling Uncertainty in Climate Change: A Multi-Model Comparison* (No. w21637). National Bureau of Economic Research.

Gleick, P.H. (2014). Water, Drought, Climate Change, and Conflict in Syria. *Weather, Climate & Society*, *6*, 331.

Gollier, C., & Hammitt, J.K. (2014). The long-run discount rate controversy. *Annual Review of Resource Economics*, *6*(1), 273-295.

Grasso, M. & Roberts, T. (2014). A Compromise to Break the Climate Impasse. *Nature Climate Change*, *4*, 543.

Greenstone, M., Kopits, E., & Wolverton, A. (2013). Developing a Social Cost of Carbon for U.S. Regulatory Analysis: A Methodology and Interpretation. *Review of Environmental Economics and Policy*, *7*, 23.

Hamilton, J.M., Maddison, D.J., & Tol, R.S. (2005). Effects of climate change on international tourism. *Climate Research*, *29*(3), 245-254.

Harden, G. (1968). The Tragedy of the Commons. *Science*, *162*, 1243.

Hendrixson, J. (2014). White House, EPA Defend Using Global Climate Benefits for GHG Proposal. *IWP News*, July 28.

Hisschemöller, M., Tol, R.S., & Vellinga, P. (2001). The relevance of participatory approaches in integrated environmental assessment. *Integrated Assessment*, *2*(2), 57-72.

Hoel, M., & Sterner, T. (2007). Discounting and relative prices. *Climatic Change*, *84*(3-4), 265-280.

Hope, C. (2006). The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated assessment*, *6*(1).

Houser, T., Hsiang, S., Kopp, R., Larsen, K., Delgado, M., Jina, A., ... & Rising, J. (2014). American climate prospectus. *Economic Risks in the United States. Rhodium Group, LLC*.

Howard, P. (2014). Omitted Damages: What's Missing from the Social Cost of Carbon. Institute for Policy Integrity Report.

Howard, P. & Schwartz, J. (2015). Foreign Action, Domestic Windfall. Institute for Policy Integrity Report.

Howard, P. & Schwartz, J. (2016, forthcoming). Think Global: International Reciprocity as Justification for a Global Social Cost of Carbon. Institute for Policy Integrity Report.

Howard, P. & Sterner, T. (2016, forthcoming). Few and Not So Far Between. Working Paper.

Howard, P., & Sylvan, D. (2015). Expert Consensus on the Economics of Climate Change. Institute for Policy Integrity Report.

Hsiang, S.M., & Burke, M. (2014). Climate, conflict, and social stability: what does the evidence say? *Climatic Change*, *123*(1), 39-55.

Hsiang, S.M., & Jina, A.S. (2014). *The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones* (No. w20352). National Bureau of Economic Research.

Hsiang, S.M., Meng, K.C., & Cane, M.A. (2011). Civil conflicts are associated with the global climate. *Nature*, *476*(7361), 438-441.

Hsiang, S.M. (2010). Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences, 107*(35), 15367-15372.

[IPCC] Intergovernmental Panel on Climate Change. (2014). Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge, United Kingdom and New York, USA*.

[IWG] Interagency Working Group on Social Cost of Carbon, United States Government. (2010). Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12,866.

[IWG] Interagency Working Group on Social Cost of Carbon, United States Government. (2013). Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12,866.

[IWG] Interagency Working Group on Social Cost of Carbon, United States Government. (2015a). Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12,866.

[IWG] Interagency Working Group on Social Cost of Carbon, United States Government. (2015b). Response to Comments: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12,866.

Johnson, L.T., & Hope, C. (2012). The social cost of carbon in US regulatory impact analyses: an introduction and critique. *Journal of Environmental Studies and Sciences*, *2*(3), 205-221.

Kelley, C.P. et al. (2014). Climate Change in the Fertile Crescent and Implications of the Recent Syrian Drought, *Proceedings of the National Academies of Sciences*, *112*, 3241.

Kopp, R.E., Golub, A., Keohane, N.O., & Onda, C. (2012). The influence of the specification of climate change damages on the social cost of carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, *6*.

Kopp, R.E. & Mignone, B. (2013). Circumspection, Reciprocity, and Optimal Carbon Prices. *Climatic Change*, *120*, 831.

Kopp, R. E., Shwom, R., Wagner, G., & Yuan, J. (2016). Tipping elements, tipping points, and economic catastrophes: Implications for the cost of climate change. *arXiv preprint arXiv:1603.00850*.

Laden, F., Schwartz, J., Speizer, F.E., & Dockery, D.W. (2006). Reduction in Fine Particulate Air Pollution and Mortality. *American Journal of Respiratory and Critical Care Medicine 173*:667-672.

Lemoine, D.M., & Traeger, C.P. (2012). *Tipping points and ambiguity in the economics of climate change* (No. w18230). National Bureau of Economic Research.

Lenton, T.M., & Ciscar, J.C. (2013). Integrating tipping points into climate impact assessments. *Climatic Change*, *117*(3), 585-59

Link, P.M., & Tol, R.S. (2011). Estimation of the economic impact of temperature changes induced by a shutdown of the thermohaline circulation: an application of FUND. *Climatic Change*, *104*(2), 287-304.

Litterman, B. (2013). What is the right price for carbon emissions. *Regulation*, *36*, 38.Lowe, J. (2008). Intergenerational wealth transfers and social discounting: Supplementary Green Book guidance. *HM Treasury, London*.

Madani, K. (2013). Modeling International Climate Change Negotiations More Responsibly: Can Highly Simplified Game Theory Models Provide Reliable Policy Insights? *Ecological Economics*, *90*, 68.

Newbold, S.C., & Marten, A.L. (2014). The value of information for integrated assessment models of climate change. *Journal of Environmental Economics and Management*, *68*(1), 111-123.

Nicholls, R.J., Tol, R.S., & Vafeidis, A.T. (2008). Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND. *Climatic Change*, *91*(1-2), 171-191.

Madrid Protocol. (1991). Protocol on Environmental Protection to the Antarctic Treaty.

Manne, A.S., & Richels, R.G. (2005). MERGE: an integrated assessment model for global climate change. In *Energy and Environment* (pp. 175-189). Springer US.

Mendelsohn, R., Morrison, W., Schlesinger, M.E., & Andronova, N. G. (2000). Country-specific market impacts of climate change. *Climatic change*,*45*(3-4), 553-569.

Moore, F.C., & Diaz, D.B. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, *5*(2), 127-131.

Moss, R.H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J. A., ... & Jones, R. (2008). *Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies* (No. PNNL-SA-63186). Pacific Northwest National Laboratory (PNNL), Richland, WA (US).

Moyer, E.J., Woolley, M.D., Glotter, M., & Weisbach, D.A. (2014). Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon. *Journal of Legal Studies*, *43*(2), 401-425.

[NAS] National Academy of Sciences. (2016). Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update.

Nelson, J.P., & Kennedy, P.E. (2009). The use (and abuse) of meta-analysis in environmental and natural resource economics: an assessment. *Environmental and Resource Economics*, *42*(3), 345-377.

Neumayer, E. (1999). Global warming: discounting is not the issue, but substitutability is. *Energy Policy, 27*(1), 33-43.

Newbold, S.C., Griffiths, C., Moore, C., Wolverton, A., & Kopits, E. (2013). A rapid assessment model for understanding the social cost of carbon. *Climate Change Economics*, *4*(01), 1350001.

Newbold, S.C., Griffiths, C., Moore, C., Wolverton, A., & Kopits, E. (2014). Further Comment On "A Rapid Assessment Model For Understanding The Social Cost Of Carbon." *Climate Change Economics*, *5*(02), 1450005.

Newbold, S.C., & Marten, A.L. (2014). The value of information for integrated assessment models of climate change. *Journal of Environmental Economics and Management*, *68*(1), 111-123.

Newell, R.G., & Pizer, W.A. (2003). Discounting the distant future: how much do uncertain rates increase valuations? *Journal of Environmental Economics and Management*, *46*(1), 52-71.

Nordhaus, W.D. (1992). An optimal transition path for controlling greenhouse gases. *Science (Washington)*, *258*(5086), 1315-1319.

Nordhaus, W.D. (1993). Optimal greenhouse-gas reductions and tax policy in the "DICE" model. *The American Economic Review*, *83*(2), 313-317.

Nordhaus, W.D. (1994). Expert opinion on climatic change. *American Scientist*, *82*(1), 45-51.

Nordhaus, W.D. (2008). A question of balance: economic modeling of global warming.

Nordhaus, W.D. (2013). *The climate casino: Risk, uncertainty, and economics for a warming world*. Yale University Press.

Nordhaus, W.D. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, *1*(1/2), 273-312.

Nordhaus, W.D. (2015). Q&A and Damage Functions. Answers prepared by William Nordhaus, Yale University, for NRC Panel on the Social Cost of Carbon, November 13, 2015.

Nordhaus, W.D., & Boyer, J. (2000). *Warning the World: Economic Models of Global Warming*. MIT Press (MA).

Nordhaus, W.D., & Sztorc, P. (2013). *Introduction and User's Manual. Available at* http://www.econ.yale.edu/~nordhaus/homepage/documents/Dicemanualfull.pdf.

Obama, B.H. (2011). Executive Order 13,563: Improving Regulation and Regulatory Review. *Federal Register*, *76,* Jan. 18.

Obama, B.H. (2012). Executive Order 13,609: Promoting International Regulatory Cooperation. *Federal Register, 77*, May 4.

Obama, B.H. (2014). Commencement Address, U.S. Military Academy at West Point, May 28.

Obama, B.H. (2015). Remarks by the President in Announcing the Clean Power Plan.

[OMB] Office of Management and Budget. (2003). Circular A-4.

[OMB] Office of Management and Budget. (2011). Regulatory Impact Analysis: A Primer.

Oosterbeek, H., et al. (2004). Cultural Differences in Ultimatum Game Experiments: Evidence from a Meta-Analysis. *Experimental Economics*, *7*, 171.

[OSMRE] U.S. Department of the Interior Office of Surface Mining, Reclamation, and Enforcement. (2015). Record of Decision: Four Corners Power Plant and Navajo Mine Energy Project.

Ostrom, E. (2014). A Polycentric Approach for Coping with Climate Change. *Annals of Economics and Finance*, *15*, 97.

Pal, J.S., & Eltahir, E.A. (2015). Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*.

Pizer, W., Adler, M., Aldy, J., Anthoff, D., Cropper, M., Gillingham, K., Greenstone, M., Murray, B., Newell, R., Richels, R., Rowell, A., Waldhoff, S., Wiener, J. (2014). Using and Improving the Social Cost of Carbon. *Science*, *346*, 1189.

[Policy Integrity et al.] Institute for Policy Integrity, Environmental Defense Fund, Natural Resources Defense Council, and Union of Concerned Scientists. (2016). Joint Comments to the Forest Service on Proposed Exception to the Colorado Roadless Rule.

Pope, C.A., III, Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., & Thurston, G.D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association 287*:1132-1141.

Rehdanz, K., & Maddison, D. (2005). Climate and happiness. *Ecological Economics*, *52*(1), 111-125.

Revesz, R. L., Howard, P.H., Arrow, K., Goulder, L. H., Kopp, R. E., Livermore, M.A., ... & Sterner, T. (2014). Global warming: Improve economic models of climate change. *Nature*, *508*(7495), 173-175.

Roman, H.A., Walker, K.D., Walsh, T.L., Conner, L., Richmond, H.M., Hubbell, B.J., & Kinney, P.L. (2008). Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the US. *Environmental science & technology*, *42*(7), 2268-2274.

Roson, R., & Van der Mensbrugghe, D. (2012). Climate change and economic growth: impacts and interactions. *International Journal of Sustainable Economy*, *4*(3), 270-285.

Rowell, A. (2015). Foreign Impacts and Climate Change. *Harvard Environmental Law Review*, *39*, 371.

[RWG] Regulatory Working Group. (2015). Guidelines on Executive Order 13,609.

Sanfey, A.G., et al. (2003). The Neural Basis of Economic Decision-making in the Ultimatum Game. *Science*, *300*, 1755.

Schauer, M.J. (1995). Estimation of the greenhouse gas externality with uncertainty. *Environmental and Resource Economics*, *5*(1), 71-82.'

Schlenker, W., Hanemann, W.M., & Fisher, A.C. (2005). Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. *The American Economic Review*, *95*(1), 395-406.

Schlenker, W., & Roberts, M.J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of sciences*, *106*(37), 15594-15598.

Schwarz, S.L. (2008). Systemic Risk. *Georgetown Law Journal*, *97*, 193.

Shelanski, H. (2013). Oral Testimony at the Hearing on Examining the Obama Administration's Social Cost of Carbon Estimates, before the House Committee on Oversight and Government Reform Subcommittee on Energy Policy, Health Care, and Entitlements, 113th Congress, 1st Session, Serial No. 113-55.

Smead, R. et al. (2014). A Bargaining Game Analysis of International Climate Negotiations. *Nature Climate Change*, *4*, 442.

Stanley, T.D., Doucouliagos, H., Giles, M., Heckemeyer, J.H., Johnston, R.J., Laroche, P., ... & Rosenberger, R.S. (2013). Meta-analysis of economics research reporting guidelines. *Journal of Economic Surveys*, *27*(2), 390-394.

Sterner, T., & Persson, U.M. (2008). An even sterner review: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy*, *2*(1), 61-76.

Steward, R.B., Oppenheimer, M., & Rudyk, B. (2013). Building Blocks for Global Climate Protection. *Stanford Environmental Law Journal*, *32*, 341.

Tol, R.S. (2002). Estimates of the damage costs of climate change. Part 1: Benchmark estimates. *Environmental and resource Economics*, *21*(1), 47-73.

Tol, R.S. (2009). The economic effects of climate change. *The Journal of Economic Perspectives*, *23*(2), 29-51.

Tol, R.S. (2013). *Bootstraps for Meta-Analysis with an Application to the Impact of Climate Change* (No. 6413).

Tol, R.S. (2014). Correction and Update: The Economic Effects of Climate Change. *The Journal of Economic Perspectives*, 221-225.

Traeger, C.P. (2014). Why uncertainty matters: discounting under intertemporal risk aversion and ambiguity. *Economic Theory*, *56*(3), 627-664.

Traeger, C.P. (2014b). A 4-stated DICE: quantitatively addressing uncertainty effects in climate change. *Environmental and Resource Economics*, *59*(1), 1-37.

United Nations Framework Convention on Climate Change (1992).

U.S. Court of Appeals for the Ninth Circuit. (2008). Center for Biological Diversity v. NHTSA, 538 F.3d 1172.

Walton, T. (2009). Regulatory Impact Analysis: National Emission Standards for Hazardous Air Pollutants from the Portland Cement Manufacturing Industry. *Final Report US Environmental Protection Agency*.

Weitzman, M.L. (2001). Gamma discounting. *American Economic Review*, 260-271.

Weitzman, M.L. (2012). GHG targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory*, *14*(2), 221-244.

White House. (2016). U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership.

Wood, P.J. (2011). Climate Change and Game Theory. *Annals of the New York Academy of Sciences*, *1219*, 153.

World Bank. (2014). ENVISAGE, http://go.worldbank.org/8DTXIDMRM0 (last visited Feb. 4, 2014).