March, 2017

Chapter 3

Estimated Values of Carbon Sequestration Resulting from Forest Management Scenarios

The Council on Food, Agricultural & Resource Economics

Authors

Synthesis Chapter - The Valuation of Ecosystem Services from Farms and Forests: Informing a systematic approach to quantifying benefits of conservation programs

Project Co-Chair: L. Wainger, University of Maryland Center for Environmental Science, Solomons, MD, wainger@umces.edu
Project Co-Chair: D. Ervin, Portland State University, Portland, OR, dervin@pdx.edu

Chapter 1: Assessing Pollinator Habitat Services to Optimize Conservation Programs

R. Iovanna, United States Department of Agriculture – Farm Service Agency, Washington, DC, Rich.Iovanna@wdc.usda.gov
A. Ando, University of Illinois, Urbana, IL, amyando@illinois.edu
S. Swinton, Michigan State University, East Lansing, MI, swintons@msu.edu
J. Kagan, Oregon State/Portland State, Portland, OR, jkagan@pdx.edu
D. Hellerstein, United States Department of Agriculture - Economic Research Agriculture, Washington, DC, danielh@ers.usda.gov
D. Mushet, U.S. Geological Survey, Jamestown, ND, dmushet@usgs.gov
C. Otto, U.S. Geological Survey, Jamestown, ND, cotto@usgs.gov

Chapter 2: Ecosystem Service Benefits Generated by Improved Water Quality from Conservation Practices

L. Wainger, University of Maryland Center for Environmental Science, Solomons, MD, wainger@umces.edu
J. Loomis, Colorado State University, Fort Collins, CO, john.loomis@colostate.edu
R. Johnston, Clark University, Worcester, MA, rjohnston@clarku.edu
L. Hansen, USDA ERS, United States Department of Agriculture - Economic Research Agriculture, Washington, DC, lhansen@ers.usda.gov
D. Carlisle, United States Geological Survey, Reston, VA, dcarlisle@usgs.gov
D. Lawrence, Blackwooods Group, Washington, DC, doug.lawrence@blackwoodsgroup.com
N. Gollehon, United States Department of Agriculture - Natural Resources Conservation Service, Beltsville, MD, noel.gollehon@wdc.usda.gov
L. Duriancik, United States Department of Agriculture - Natural Resources Conservation Service, Beltsville, MD, lisa.duriancik@wdc.usda.gov
G. Schwartz, U.S. Geological Survey, Reston, VA, gschwarz@usgs.gov
M. Ribaudo, United States Department of Agriculture - Economic Research Agriculture, Washington, DC, mribaudo@ers.usda.gov
C. Gala, Council on Food, Agricultural and Resource Economics, Washington, DC, cgala@cfare.org

Chapter 3: Estimated Values of Carbon Sequestration Resulting from Forest Management Scenarios

R. Bluffstone, Portland State University, Portland, OR, bluffsto@pdx.edu
J. Coulston, United States Department of Agriculture - US Forest Service, Blacksburg, VA, jcoulston@fs.fed.us
R.G. Haight, United States Department of Agriculture - US Forest Service, St. Paul, MN, rhaight@fs.fed.us
J. Kline, United States Department of Agriculture - US Forest Service, Corvallis, OR, jkline@fs.fed.us
S. Polasky, University of Minnesota, St. Paul, MN, polasky@umn.edu
D.N. Wear, United States Department of Agriculture - US Forest Service, Raleigh, NC, dwear@fs.fed.us
K. Zook, United States Department of Agriculture – Office of the Chief Economist, Washington, DC, kzook@oce.usda.gov

Project Director: Caron Gala, Council on Food, Agricultural and Resource Economics

Acknowledgements

A special thanks to Chris Hartley, Steven Kraft, Roger Coupal, J.B. Ruhl, Sara Mason, Lydia Olander, Silvia Secchi, and Rob Winthrop who provided guidance and advice throughout the duration of the project. We also appreciate thoughtful review comments on the team reports by Rich Adams, David Cleaves, Jan Lewandrowski, Jeff Prestemon, J.B. Ruhl, David Simpson, and Brent Sohngen.

Disclaimer

The views expressed are those of the authors and should not be attributed to the USDA Economic Research Service, USDA Farm Service Agency, USDA Natural Resources Conservation Service, U.S. Forest Service, U.S. Geological Survey, or the U.S. Department of Agriculture Office of the Chief Economist. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Please note, the report and its chapters are intended to demonstrate a framework approach to ecosystem service valuation. The report or any chapter there within is not to be cited for the purpose of supporting or opposing any government or private program.

Suggested Citation

Wainger, L. and D. Ervin (editors). 2017. Synthesis Chapter - The Valuation of Ecosystem Services from Farms and Forests: Informing a systematic approach to quantifying benefits of conservation programs. The Council on Food, Agricultural and Resource Economics (C-FARE) Report No. 0114-301, Washington DC (March; available at http://www.cfare.org/publications/valuing-ecosystem-services-from-farms-and-forests).

Individual Chapters

Wainger, L. and D. Ervin. 2017 Synthesis Chapter - The Valuation of Ecosystem Services from Farms and Forests: Informing a systematic approach to quantifying benefits of conservation programs. The Council on Food, Agricultural and Resource Economics (C-FARE) Report No. 0114-301a, Washington DC (March; available at http://www.cfare.org/publications/valuing-ecosystem-services-from-farms-and-forests).

Iovanna, R., A. Ando, S. Swinton, D. Hellerstein, J. Kagan, D. Mushet, and C. Otto. 2017. Chapter 1: Assessing Pollinator Habitat Services to Optimize Conservation Programs. The Council on Food, Agricultural and Resource Economics (C-FARE) Report No. 0114-301b, Washington DC (March; available at http://www.cfare.org/publications/valuing-ecosystem-services-from-farms-and-forests).

Wainger, L., J. Loomis, R. Johnston, L. Hansen, D. Carlisle, D. Lawrence, N. Gollehon, L. Duriancik, G. Schwartz, M. Ribaudo and C. Gala. 2017. Chapter 2: Ecosystem Service Benefits Generated by Improved Water Quality from Conservation Practices. The Council on Food, Agricultural and Resource Economics (C-FARE) Report No. 0114-301c, Washington DC (March; available at http://www.cfare.org/publications/valuing-ecosystem-services-from-farms-and-forests).

Bluffstone, R., J. Coulston, R.G. Haight, J. Kline, S. Polasky, D.N. Wear, and K. Zook. 2017. Chapter 3: Estimated Values of Carbon Sequestration Resulting from Forest Management Scenarios. The Council on Food, Agricultural and Resource Economics (C-FARE) Report No. 0114-301c, Washington DC (March; available at http://www.cfare.org/publications/valuing-ecosystem-services-from-farms-and-forests).

This page was intentionally left blank.

This page was intentionally left blank.

Contents

Estimated Values of Carbon Sequestration Resulting from Forest Management Scenarios

R. Bluffstone, Portland State University, Portland, OR, bluffsto@pdx.edu
J. Coulston, United States Department of Agriculture - US Forest Service, Blacksburg, VA, jcoulston@fs.fed.us
R.G. Haight, United States Department of Agriculture - US Forest Service, St. Paul, MN, rhaight@fs.fed.us
J. Kline, United States Department of Agriculture - US Forest Service, Corvallis, OR, jkline@fs.fed.us
S. Polasky, University of Minnesota, St. Paul, MN, polasky@umn.edu
D.N. Wear, United States Department of Agriculture - US Forest Service, Raleigh, NC, dwear@fs.fed.us
K. Zook, United States Department of Agriculture – Office of the Chief Economist, Washington, DC, kzook@oce.usda.gov

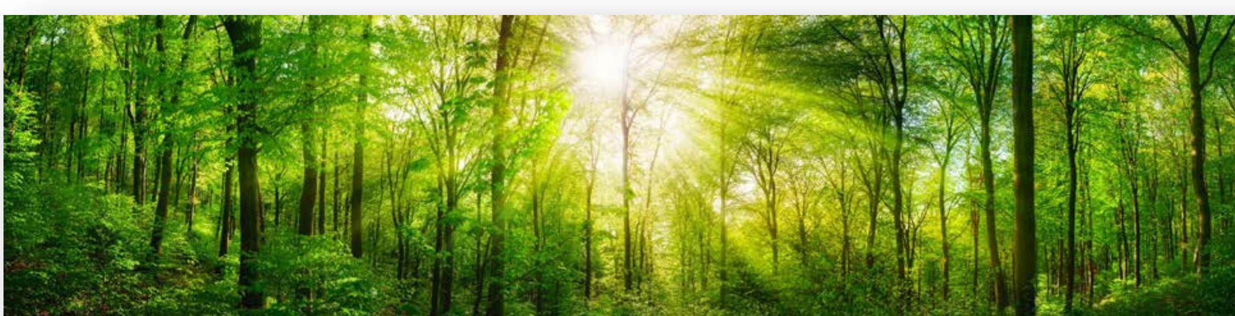
Abstract
Recent USDA policies, such as the Building Blocks for Climate Smart Agriculture and Forestry, aim to sequester and mitigate greenhouse gases in the forestry and agriculture sectors in the United States. To make informed decisions, the USDA will need to evaluate the carbon benefits of various potential policies. In this paper, we use detailed forest inventory data to project the carbon impacts of a range of modeled policies through 2060: 1) a policy resulting in reduced deforestation due to development, 2) a policy combining a Conservation Reserve Program (CRP) afforestation policy targeting private forestland in the eastern U.S. with a reforestation policy targeting historically understocked acres on federal forests in the western U.S., and 3) a policy that reduces the rate of stand-replacing fire events by 10 percent. We then apply the social cost of carbon (SCC) to the carbon benefits of each policy to estimate the value of carbon associated with the policy scenarios. The analysis finds that a policy targeting both afforestation on private land in the Eastern U.S. and reforestation on public land in the Western U.S provides the largest dollar carbon benefit, with a present value of about $649 billion at a three percent SCC discount rate, and an increase in the present value over the reference scenario of $131.6 billion. This analysis demonstrates the carbon value to society provided by potential USDA policies. Future analysis should include policy costs, and consider the additional costs and benefits of ecosystem services such as those associated with water quality, habitat, and biodiversity.

Introduction
Current USDA policy includes, among other goals, an intention to lead efforts to mitigate and adapt to climate change, drought, and extreme weather in agriculture and forestry (U.S. Department of Agriculture 2014). The Department envisions addressing these goals by encouraging conservation of sensitive lands, private forest growth and retention, and stewardship of federal forests, among other policy goals outlined in the USDA's Building Blocks for Climate Smart Agriculture and Forestry strategy (U.S. Department of Agriculture 2016). Approaches for meeting these goals could involve increasing stored carbon with USDA incentive programs targeting agricultural and forest lands to retain, increasing afforestation of especially marginal agricultural lands, and altering the management of existing nonindustrial forestlands, among other policy and program alternatives (e.g., Lewandrowski et al. 2004, McKinley et al. 2011, Khanal et al. in press). Evaluating the potential effects of incentive programs on forest carbon and associated ecosystem services thus is of growing interest as policies for increasing carbon storage are being proposed for both public (e.g.,

Ellenwood et al. 2012) and private lands (e.g., Latta et al. 2016). Evaluating potential USDA policy and program effects on stored carbon, however, requires the development of suitable and consistent performance metrics that can be used to track progress toward meeting USDA goals in national-level performance reporting. This includes metrics for characterizing the amount of stored carbon increase (or decrease) resulting from agency policies and programs. In this chapter, we develop a conceptual value diagram and demonstrate a method for evaluating stored carbon in response to USDA policies and programs, with a focus on restoration of public forestlands, enhanced management of private forestlands, and afforestation of private agricultural lands.

Specifically, we draw on existing data and models to develop a national-level measure of forest carbon and its value. We use that measure to estimate future changes in forest carbon and its value (in dollars) likely to result under different land use (e.g., afforestation and reforestation) and forest disturbance (e.g., wildfire) scenarios. Increased carbon storage on forest lands, or expansion of forest lands via afforestation, can also often involve notable changes in other valued ecosystem services, including water quality, habitat for terrestrial and aquatic species, and provision of timber, just to name a few, with increased carbon storage accompanied by increases in the provision of complementary services and decreases in more competitive services (e.g., Englin and Callaway 1995, Kline et al. 2016). Enhancing many of these other ecosystem services has long been a part of USDA policies and programs (e.g., Claassen et al. 2001). We chose not to attempt to address changes in other ecosystem services, to focus on a key element of the USDA's overall climate change strategy—increasing stored forest carbon to mitigate climate change. We feel that adequately addressing the degree to which other ecosystem services would be either enhanced or reduced by carbon storage policies and programs represents a larger scale research effort than can be accomplished within the specific interests of this analysis. Instead, we focus on one piece of the USDA's overall strategy to mitigate GHG emissions in the agriculture and forestry sectors: forest carbon.

Our approach is: first, to connect USDA actions to ecological outcomes (in this case, the modeled quantity of carbon stocks resulting from changes in USDA policies), and second, to connect those carbon outcomes with dollar values (using the Social Cost of Carbon, which is explained in more detail below). Our conceptual value diagram is depicted in Figure 1 below, using two modeled policies as examples. The first of those is a Carbon Reserve Program (CRP)-like policy representing afforestation on privately held acres in the eastern U.S. The second is a federal land policy representing reforestation on publicly held acres that have been persistently understocked in trees in the western U.S. After modeling and quantifying the increase in carbon stocks resulting from these policy changes, we apply the social cost of carbon to estimate the dollar value of carbon benefits to society accrued.



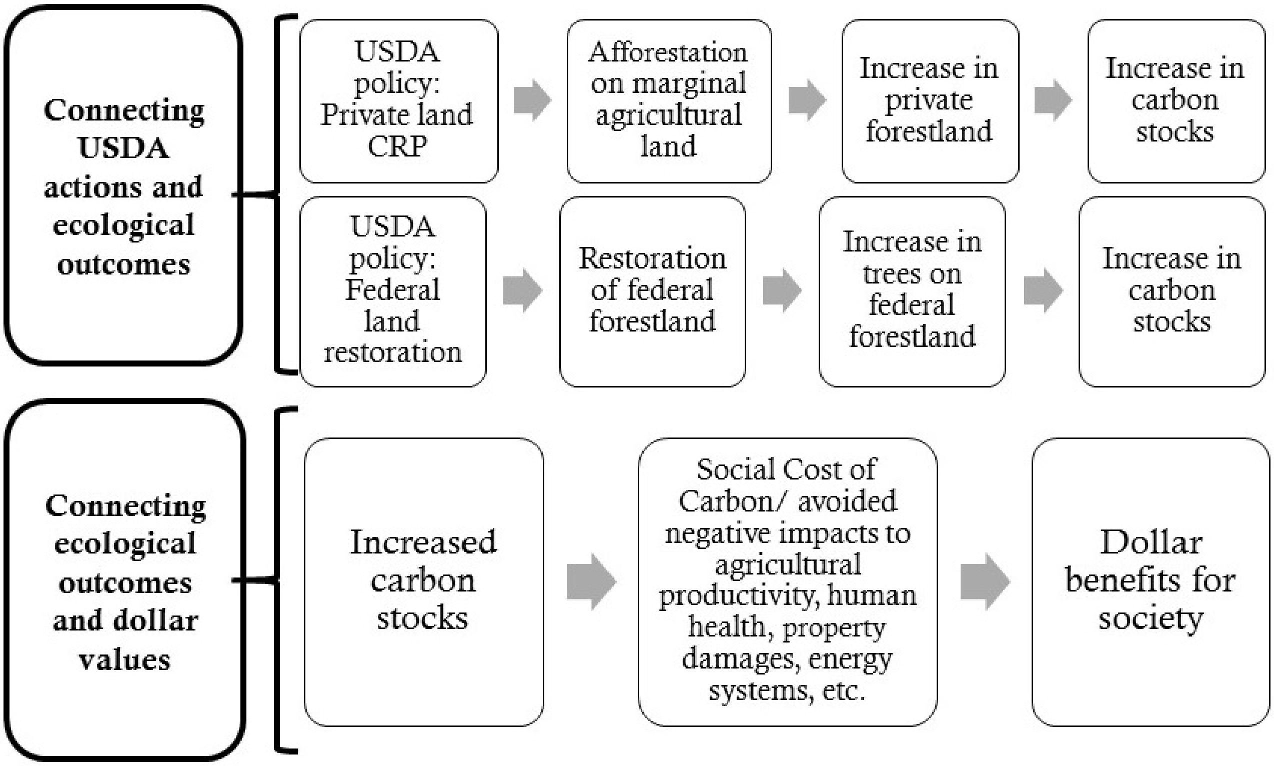


Figure 1. Conceptual value diagram demonstrating the two-step approach described in this paper.

Quantifying and Projecting Forest Carbon

Our estimates of current forest carbon stocks and sequestration potential for the U.S. rely on empirical data from the USDA Forest Service's Forest Inventory and Analysis (FIA) Program (O'Connell et al. 2014). These data are based on observations from over 350,000 permanent monitoring locations (or plots) across the coterminous United States and provide estimates of current forest carbon pools: live tree carbon above ground, live tree carbon below ground, deadwood carbon, litter layer carbon, and soil organic carbon. Observed transitions of FIA plot conditions provide estimates of land use change, forest disturbance, and forest management on forest carbon and serve as the basis for parameterizing empirical projection models.

Wear and Coulston (2015) provide the framework for using these data to project future land use and forest carbon. The primary components of their projection framework include carbon densities by forest age class, forest sequestration rates by age class, areal extent of forest by age class, and age transition probabilities aggregated at the state or regional level. Wear and Coulston (2015) use different approaches for the western and eastern United States. In the western U.S., they model changes in forest carbon using inventory aggregates and a stage-class forest population model. This model applies a transition matrix, in which the elements of the matrix depend on factors that include forest disturbances such as harvests, fire, and storms, to estimate changes in forest carbon. In the eastern U.S., Wear and Coulston (2015) use remeasured inventory plots based on simulated forest types and age transitions, using average carbon for given forest age categories.

For most of the forests in the United States, empirical data on age transitions based on plot remeasurements (including disturbance and management effects) are used to calculate area age transition probabilities. In areas where remeasured data were not yet available, age transition probabilities are inferred from current age distributions.

Forest dynamics (aging, disturbance, management) are applied as transition probabilities to current estimates of areal extent by age, and define changes in forest structure. Carbon sequestration is then estimated using observed carbon stock densities and estimated sequestration rates applied to the new forest structure. Land use shifts are integrated into the system using either theoretical or observed land use transition probabilities, depending on whether remeasured data were available. Disturbance is integrated similarly. For details on these projection models, refer to Wear and Coulston (2015). Similar methods could be replicated to reproduce these results using updated FIA and U.S. National Greenhouse Gas Inventory data.

Valuing Carbon

Carbon storage by U.S. forests is valuable, because carbon that would otherwise have been emitted into the atmosphere as CO_2 or other greenhouse gases, causing climate change, is instead trapped in living trees. This process is known as sequestration. Sequestration, therefore, helps reduce CO_2 concentrations, reducing the negative effects of climate change. The reduction of these negative effects on people and the planet provide the economic benefit of carbon stored by forests. Rhodium Group (2014) discusses some of the economic damages from climate change in the U.S. These include increased cooling costs because of higher temperatures, damage to property from flooding and more severe storms, reduced agricultural yields due to drought, and increased water storage costs in the west due to reduced snowpack.

Estimating the value of the economic benefits of carbon stored in U.S. forests requires two inputs: 1) the amount of carbon stored in U.S. forests, and 2) the value per ton of carbon sequestered in U.S. forests. The value per ton can be expressed in a variety of units, but often monetary units are especially helpful, because then the value per ton can be compared with dollar costs (either direct expenditures or benefits given up when land is retained as forests) of policies and programs. The unit value is not immediately apparent for several reasons, including that most of the damages avoided by sequestering a ton of carbon are not traded in markets and therefore do not have monetary prices. Avoided damages are also not known with certainty, which implies that the value of carbon sequestration is not known for sure.

When a ton of CO_2 is sequestered, it not only mitigates contemporary climate change, but also avoids causing damages for the life of the sequestration. Therefore, values need to be estimated over this full-time span and presented as present values. A “discount rate” is needed to put all future benefits in present value terms. The discount rate embeds conditions that tend to make long-term returns less valuable than near-term returns, when viewed from the present time. Those conditions include societal impatience for returns, the effect of economic growth over time on the value of money, and other social and economic factors (Arrow et al. 2014).

Because the value of carbon sequestration is estimated as avoided social costs, the unit value of a ton of carbon dioxide sequestered is typically referred to as the “social cost of carbon” (SCC). SCC estimates are generally applied to emissions, are denominated in monetary units, and are forecast using integrated climate-economy simulation models called integrated assessment models (IAMs).

In 2009, the U.S. government convened an interagency working group to estimate the SCC, and it is the set of SCC estimates from this interagency working group that we use in this report. The authors of the reports assumed a global SCC perspective, because carbon is a uniformly distributed pollutant around the globe, and they used estimates from the three major IAMs. The processes, updates, and results of these estimates are described by the U.S. Interagency Working Group (2010, 2013, 2015) and the methods used in the 2010 report are summarized in Greenstone et al. (2013). The Interagency Working Group estimated a nominal 2010 central SCC value of $21 per additional ton of CO_2 sequestered (emitted) measured in $U.S. 2007. Economic effects of climate change included effects on “agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services” (Greenstone et al., 2013).

There are three IAMs that are commonly used to forecast the SCC. The Dynamic Integrated Climate Economy (DICE) model was developed by William Nordhaus of Yale University (Nordhaus, 1992). The Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model was developed by Richard Tol of the University of Sussex (Tol, 1999) and the Policy Analysis of the Greenhouse Effect (PAGE) model was developed by Chris Hope of Cambridge University (Hope et al., 1993). These models have different sets of assumptions and, not surprisingly, produce different results. They are also amended, adapted, and revised depending on the specific objectives of a given application, and can be applied at a variety of scales, including globally.

The key estimates from the Interagency Working Group (2010) were revised in 2013, and again in 2015, using updated versions of the DICE, PAGE, and FUND models. The Group did not revise the baseline assumptions, and in all three reports the authors present values that assume four different discount rates. The authors of these reports used a three percent annual discount rate to estimate their central values.

Table 1 below reproduces the estimates from the Interagency Working Group (2015) with the three percent discount rate estimates considered central values. Values are updated from $U.S. 2007 to $U.S. 2016 using the consumer price index. The SCC estimates increase over time, because the CO_2 concentrations in the atmosphere are expected to increase over time and because higher concentrations imply greater damages per additional ton emitted. Because the effects of climate change are anticipated to be worse over time, sequestering carbon in the future mitigates more damages than sequestration in the present. Therefore, the estimated value of sequestering CO_2 increases over time.

To estimate the impacts of carbon in the future, we first need to estimate a scenario that projects our best estimate of how the future will look. The baseline or business-as-usual carbon emissions time path is a key input into such models. Additional damages in the future depend on greenhouse gas concentrations at any point in time, which depend on previous emissions. Also, because forecasts are reported as quantities and values over many years, a key assumption in SCC estimates is the rate at which to discount future damages back to the time of emissions or, in the case of carbon sequestration, avoided emissions (Arrow et al. 2014). Modelers also make assumptions about climate sensitivity, as well as the economic threats posed by climate change and the resulting human adaptation. As many climate change threats are uncertain, modelers must decide to what degree, and how, risks are incorporated into IAMs.

As part of its work, the Interagency Working Group conducted stochastic simulations focusing on equilibrium climate sensitivity (ECS), which is the average surface temperature increase to be expected from a doubling of CO_2 concentrations in the atmosphere. This responsiveness of the Earth to CO_2 is uncertain, but it is a key parameter underlying the integrated assessment models used to estimate SCC. After consultation with Intergovernmental Panel on Climate Change (IPCC) experts, the authors of the report concluded that the ECS lies between two and 4.5 degrees Celsius, though it is not possible to rule out values above zero degrees or below 10 degrees. The authors simulate ECS using four possible left-skewed probability distributions, but choose what is called a “Roe and Baker distribution” as most appropriate (Greenstone et al. 2013). Columns 2–4 in Table 1 present SCC values using the mean ECS of three degrees Celsius with three possible annual discount rates.

Column 5 in Table 1 uses the 95th percentile of the ECS distribution, which represents the case in which the ECS turns out to be more sensitive than only five percent of possible outcomes. This scenario is intended to show what would happen to the SCC if the central discount rate value (three percent) is used, but the climate changing effects of CO_2 emissions turn out to be much stronger than expected. Because of this greater-than-mean ECS, the economic damages are larger and SCC estimates are about three times greater than the central value estimates in Table 1.

Table 1. Nominal SCC estimates ($U.S. 2016) per Ton of CO_2 Sequestered (Emitted)

	Average Annual Discount Rate			
YEAR	5%	3%	2.5%	3% discount rate and 95th percentile Equilibrium Climate Sensitivity (ECS)
2015	$13	$42	$65	$121
2020	$14	$49	$72	$142
2025	$16	$53	$79	$160
2030	$19	$58	$84	$176
2035	$21	$64	$90	$194
2040	$24	$69	$97	$212
2045	$27	$74	$103	$228
2050	$30	$80	$110	$245

Source: U.S. Interagency Working Group (2015). The CPI is estimated by the Bureau of Labor Statistics to have increased by 15.69 percent between June 2007 and June 2016. See Table 24 from the June 2016 CPI Detailed Report, at http://www.bls.gov/cpi/cpid1606.pdf, for details.

SCC estimates for other countries also exist, most of which are higher than the U.S. values. Table 2 presents estimates over four time frames for select Organization for Economic Cooperation and Development (OECD) countries reported as “carbon values” in Smith and Braathen (2015).

Table 2. Carbon Values per Ton of CO_2e ($U.S. 2014) for* ex ante *Evaluations of Public Policies

Country	2014	2020	2030	2050
Canada	$39	$46	$56	$77
France	$53	N/A	$133	$319
Germany	$133	$159	$206	$365
Ireland	$24	$52	N/A	N/A
United Kingdom	$95	$105	$122	$348
United States	$41	$48	$57	$78

Source: Smith and Braathen (2015)

METHODS

For this effort, we build upon the work of Coulston and Wear (USDA, 2016), which projects forest carbon sequestration associated with a variety of modeled policies, by applying the SCC to those projections to determine an estimated carbon value resulting from the policies. These policies represent a variety of actions the USDA could take to increase carbon stocks in the United States. This technique allowed us to both 1) connect USDA actions to ecological outcomes (using the projections of Coulston and Wear), and 2) connect ecological outcomes and dollar values (using the SCC). This section describes both of those steps in more detail.

Policy scenarios for enhancing carbon sequestration in U.S. forests

Using detailed forest inventory data and a model of forest carbon dynamics, Coulston and Wear (USDA, 2016) build upon their previous work (2015) by projecting carbon sequestration in forests of the coterminous U.S. over a 45-year horizon (2015–2060). Their reference scenario is a projection developed for the 2016 U.S. Biennial Report by the USDA (USDA, 2016). Assuming no policy intervention, the reference scenario projects that annual carbon sequestration will decrease from 480 Tg CO_2eq yr^{-1} in 2015 to 303 Tg CO_2eq yr^{-1} in 2060, largely due to the combination and interaction among forest aging, forest disturbance, and land use change.

Coulston and Wear (USDA, 2016) also project the effects of several USDA policies intended to boost forest carbon sequestration, including reducing forest conversion due to development, increasing afforestation and reforestation, and reducing wildfire. Those policies are explained in Table 3 below. Coulston and Wear (USDA, 2016) find that, relative to the reference scenario, avoiding forest conversion and dramatically increasing afforestation and reforestation likely would result in the largest incremental forest carbon gains, increasing cumulative sequestration by 26 percent between 2015 and 2060. Wildfire mitigation was found to have a relatively minor influence on overall carbon dynamics. A summary of the projected annual carbon sequestration in forests of the coterminous U.S. under different policy scenarios is presented in Figure 2 below.

Table 3. Summary of Policy Scenarios (USDA, 2016)

Scenario Name	Description
Reference	Elimination of forest net gains in the next decade followed by a slight decline in forest area through 2060
Reduced development*	Reduced development and no net loss of forest area beginning in 2025
High (afforestation and reforestation)	• FCRP-like policy representing afforestation on 30 million acres in the eastern U.S. • Federal land policy representing reforestation on 14 million acres persistently understocked in trees in the western U.S.
High/fire	A 10% reduction in high severity fire occurrence throughout the U.S.

*The reduced development scenario is described on pages 6–8 of the Projections through 2060 document at USDA CCPO. The year 2025 is used because we assume that the USDA follows and achieves the Building Blocks goal of reducing annual emissions 120 MMt CO_2e by 2025. See also the USDA mitigation policy described at http://www.usda.gov/oce/climate_change/mitigation.htm.

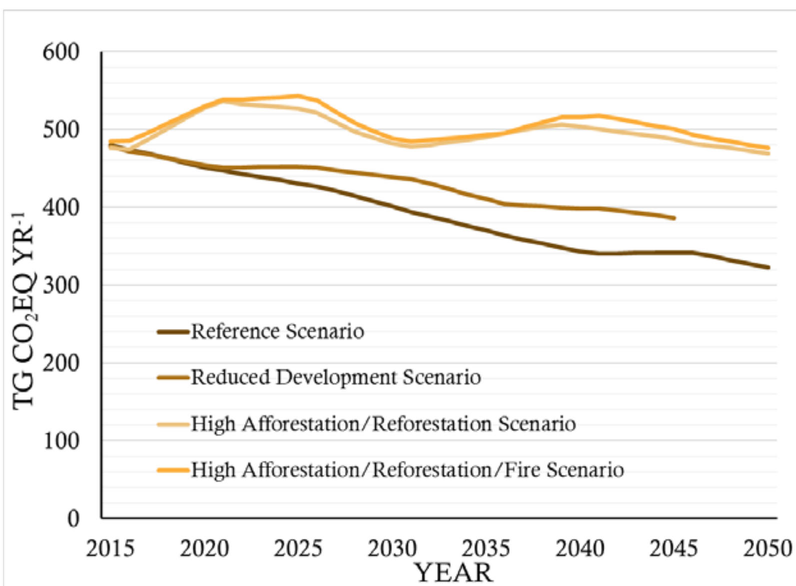


Figure 2. Projected annual carbon sequestration in forests of the coterminous U.S. under different policy scenarios (USDA 2016).

As discussed in the previous section, SCCs are nominal (i.e., undiscounted) values of the damages avoided when a ton of CO_2 that would have been emitted in a year is instead sequestered. For example, the central SCC value of a ton of CO_2 sequestered in 2030 is $58, while in 2050 it is $80. To make these and all time-dependent values comparable, we must take account of societal (including policymaker) impatience and the effect of incomes that grow over time, by discounting these values back to a base year. We discount all values to 2016 using the same discount rates that are used in the indicated SCC scenario (5.0 percent, 3.0 percent, and 2.5 percent).

In principle, the discount rates used to analyze forest policies need not be the same rates used to examine climate change damages over time. We choose to use the same rates, because policymaker decisions regarding forests are likely to be increasingly influenced by the importance of the climate change challenge. We therefore see climate change damage discount rates as most appropriate.

We estimate present values (PV) of increases in forest carbon sequestration associated with three of the policy scenarios projected by Coulston and Wear (USDA, 2016). We start with their reference scenario, add a policy that reduces development and forest conversion, add an increased afforestation and restoration policy, and finally add a fire mitigation policy (Table 4). The increase in the PV of carbon sequestration under each of the three policy scenarios relative to the PV of carbon sequestration under the reference scenario is an estimate of the carbon storage value of the policy. Because the policy scenarios are constructed in an additive fashion, we also estimate the incremental change in PV for each additional policy component.

Table 4. Definition of the reference and policy scenarios used to estimate the present value of the increase in forest carbon sequestration. See notes for explanation of policy components. From Coulston and Wear (USDA 2016).

	Scenario components		
Scenario label	Land use scenario	Afforestation + restoration policy	Fire mitigation policy
Reference	Reference		
Reduced development	Low development		
High (afforestation and reforestation)	Low development	High	
High/fire	Low development	High	Yes

Estimating the value of forest carbon sequestration

To compute the present value of the stream of carbon sequestration benefits under any one of the three policy scenarios relative to a reference scenario, we need three sets of parameter values. Let $C_1(t)$ and $C_2(t)$ be the Tg CO_2eq sequestered (Tg, teragrams, one million metric tons) in period t for the reference and policy scenarios, respectively. Let $SCC(t)$ be the social cost of carbon: the present value ($ per ton CO_2) of removing one metric ton of CO_2 from the atmosphere in period t. This is determined as the discounted value of the annual contribution to damage caused by one metric ton of CO_2 released in period t, summed over the expected number of years that the unit of CO_2 is present in the atmosphere, and discounted to period t. Let r be the discount rate used to discount the nominal values of SCC back to the base year $t = 0$. Then, the present values of the reference and policy scenarios ($ million), computed over a T-period planning horizon, are:

$$PV_1 = \sum_{t=0}^{T} \frac{SCC(t)C_1(t)}{(1+r)^t}$$

Equation 1. Reference scenario.

$$PV_2 = \sum_{t=0}^{T} \frac{SCC(t)C_2(t)}{(1+r)^t}$$

Equation 2. Policy scenario.

The difference, PV_2 - PV_1, is an estimate of the additional value of carbon sequestered under the policy scenario. This difference in PV assumes that the activities and resulting carbon sequestration in the policy scenario are additional, reducing atmospheric CO_2 beyond what would occur in the reference scenario without the policy. Further, we assume that the activities that promote carbon sequestration in the policy scenario do not affect activities and carbon emissions in other sectors (i.e., there is no leakage). For example, leakage occurs when an afforestation policy that converts marginal agricultural land to forest at the same time results in forest conversion of other areas to make up for portions of the afforested agricultural land. When our assumptions of additionality and no leakage are violated in practice, then our computation of the difference, PV_2 - PV_1, is an overstatement of the value of a policy to promote forest carbon sequestration. It should be noted that costs of administering the policy are not considered here; we are only valuing the policies' benefits in terms of carbon. We will address these issues in the discussion.

We compute the PVs of the reference and policy scenarios in Table 4 using vectors of annual carbon sequestration (Tg CO_2eq yr^{-1}, 2015–2050) obtained from Coulston and Wear (USDA, 2016) and plotted in Figure 2. We use a 35-year horizon because SCC levels are projected only through 2050. For each of the reference and policy scenarios in Table 4, we made four PV calculations using the four SCC scenarios in Table 1. First, for each SCC scenario, we computed a vector of annual SCC levels ($ per t CO_2) for years 2015–2050 by interpolating between the SCC estimates for the 5-year intervals in Table 1. We then multiplied the vectors of annual carbon sequestration and SCC together, as depicted in the PV equations above. Finally, as is show in the equations, we discounted each product to the base year, and summed to get the total PV ($ million).

RESULTS

Our results demonstrate that there is a high value associated with the impact of both current (i.e., reference) and hypothetical modeled policies on U.S. forest carbon. Regardless of the modeled scenario, our results show that changes in USDA policy can have a large effect on the value of carbon stored in U.S. forests. Table 5 below displays the present value of projected annual CO_2e sequestered in U.S. forests under the suite of policy scenarios.

Table 5. Present value ($ billion) of projected annual CO_2e sequestered in U.S. forests from 2015 to 2050 under alternative forest carbon policy and social cost of carbon scenarios.

	SCC scenario			
Policy scenario	5%	3%	2.50%	3% and 95th Percentile
Reference	125.5	517.3	806.7	1551.8
Reduced development	134.0	555.4	866.8	1668.0
High (afforestation and reforestation)	155.4	649.0	1013.9	1951.4
High/fire	158.0	660.1	1031.4	1985.0

The reference scenario, representing an elimination of forest net gains in the next decade followed by a slight decline in forest area through 2060 (USDA, 2016), resulted in forest carbon values ranging from $125.5 billion at a five percent discount rate to over $1,551 billion at a 95th percentile of the Roe and Baker distribution with the central discount rate value (three percent). These values indicate that, at a minimum, maintaining current land use and forest policy has a clear value to society, especially when forest projections estimate a decline in forest carbon over the next several decades. It should be noted that we did not estimate the cost of continuing to administer current forest policies—however, the carbon benefits that such policies provide are substantial.

The reduced development scenario, representing changes in land development in response to a growing U.S. population and economy, anticipates reduced development and no net loss of forest area beginning in 2025 (USDA, 2016). The carbon values estimated in this scenario range from $134 billion at a discount rate of five percent, to $555.4 billion at a central discount rate of three percent, to $1,668 billion at a 95th percentile scenario discounted at three percent. This policy, aimed at reducing forest conversion, results in an increase in present value over the reference scenario of about $38 billion at the central three percent discount rate (Table 6). This suggests that there is significant value in using policy to minimize development effects on forest cover over the next 50 years.

The third scenario (labeled "High" in Tables 3, 4, 5, and 6), combines two policies, targeting both private land in the eastern U.S. and public land in the western U.S. The first policy, representing afforestation on 30 million acres in the eastern U.S., mimics a Conservation Reserve Program (CRP)-like program by incentivizing landowners to retire and afforest marginal agricultural lands. The cap on CRP at its peak reached over 36 million acres, and is currently at about 24 million acres (Wear and Coulston, 2015). The second policy represents reforestation on acres that remain persistently understocked in trees on federal forests in the west. There are about 9.2 million acres in this category, and the modeled reforestation policy represents reforesting 80 percent of these acres (Wear and Coulston, 2015). Applying these additional policies results in carbon value estimated at about $649 billion at a three percent discount rate, with an increase in present value over the reference scenario of $131.6 billion. This policy combination presents the largest valued opportunity out of all the scenarios, suggesting that there is a high value to increasing USDA policy emphasis on afforestation and reforestation.

The final scenario ("High/fire") represents adding a policy to the "High" scenario resulting in a 10 percent reduction in high severity fire occurrence throughout the U.S. by reducing the rate of stand-replacing fire events by 10 percent and adjusting carbon among forest pools consistent with observed fire/no fire distributions in the Inventory. Adding this scenario results in a present value of $660.1 billion at the central discount rate, and $142.8 billion present value above the reference scenario at this discount rate. This scenario generates the smallest marginal gain in value, suggesting that fire suppression alone would not yield high benefits when the goal is carbon sequestration.

Table 6. Increase in present value ($ billion) of each forest carbon policy relative to the reference scenario under alternative social cost of carbon scenarios.

Policy scenario	**SCC scenario**			
Reference	5%	3%	2.50%	3% and 95th Percentile
Reduced development	8.4	38.0	60.1	116.1
High (afforestation and reforestation)	29.8	131.6	207.2	399.5
High/fire	32.4	142.8	224.6	433.1

Although the values of forest carbon sequestration resulting from this analysis are high, they are not unreasonable when presented per acre. For example, the "High" scenario, representing policies that impact both private land afforestation and public land restoration, amounts to a carbon benefit of about $830.00 per acre at the three percent discount rate over the estimated 768 million acres of forestland in the U.S., added to the additional ~14 million acres under the CRP and reforestation policies included in this scenario (Forest Inventory and Analysis, 2016). Similarly, the combination of policies, including the fire suppression scenario, amounts to approximately $844.00 per acre at the same discount rate. These values demonstrate that the carbon benefit of USFS policies could be estimated to inform choices for current and future afforestation and reforestation programs.

Summary and Discussion

Additional Costs and Benefits - Co-Benefits

Our analysis has focused on evaluating estimated changes in stored carbon resulting from USDA policies, and has not addressed potential changes to other valued ecosystem services that may accompany the changes in stored carbon. These other ecosystem services could include changes in water quality associated with affected landscapes, changes in habitat for terrestrial and aquatic species, changes in resource outputs such as timber and wood fiber, as well as changes to numerous other ecosystem services. Regional analysis of forest management effects on stored carbon suggest that increased carbon storage can be associated with increases in some services and decreases in others (e.g., Seidl et al. 2006, Schwenk et al. 2012, McLaughlin 2013, Kline et al. 2016). In analysis from the U.S., for example, Schwenk et al. (2012) found that forest management prescriptions resulting in greater carbon storage in their Vermont study site also resulted in reduced timber harvest. In western Oregon, Kline et al. (2016) found that forest management regimes resulting in increased stored carbon can lead to increases in species favoring late successional forest conditions, decreases in species favoring more open conditions, and highly variable responses for species that depend on spatial patterns of key ecological conditions, such as edge contrast involving tree heights, among others.

Similarly, afforestation can also affect a range of other ecosystem services, both positively and negatively. For example, Mckinley et al. (2011) have suggested that although afforestation of agricultural and grasslands is generally associated with improved water quality, it can reduce water quantity (e.g., streamflow), because trees uptake more water than crops or grass cover (p. 1915), although effects are known to vary by location, and in some cases, that variation can be substantial. Plantinga and Wu (2003) found that conversion of agricultural lands to forest via afforestation programs reduces externalities associated with agricultural land, such as soil erosion, as well as bringing about improvement in wildlife habitat roughly commensurate with the costs of administering such programs. Afforestation co-benefits, including species diversity, generally are enhanced where seedlings are established on lands that historically featured forest cover, with the greatest improvements to wildlife habitat and biodiversity occurring with plantings of native species (McKinley et al. 2011:1915).

Although the potential co-benefits and costs associated with other ecosystem services undoubtedly should be an important consideration in evaluating the efficacy of USDA efforts to increase stored carbon, we elected not to attempt to address changes in other ecosystem services, largely because of the complexity of doing so at a national scale. We suggest that such effects are likely to be highly variable across regions and localities, as well as across the spatial and temporal scales at which they are examined. For these reasons, we suspect that evaluating potential co-benefits (and costs) resulting from associated changes in other ecosystem services may be more feasible at regional scales or at the national forest level. Alternatively, opportunities may exist to draw on national-level analysis of other ecosystem services addressed in this broader report, to augment our own analysis of stored carbon.

Additional Costs and Benefits - Policy Costs

Additionally, our analysis has not considered the fiscal and opportunity costs associated with the policies and programs that define our scenarios. Ideally, these costs would be included in any analysis considering the efficacy of policy and program options evaluated, such as would be accomplished in a cost-benefit analysis (e.g., Mishan and Quah 2007). Such an analysis would be necessary to estimate whether the net gains in stored carbon resulting from the policy and programmatic scenarios examined are worth the investment necessary to achieve those gains. However, undertaking a full cost-benefit analysis was beyond the scope of our study.

One thing to consider when thinking about likely costs is that our baseline scenario itself is the result of an array of policies and programs, and market forces, that have affected changes in land use and forest cover in the decades leading up to the present. These factors have exerted influence at a variety of spatial scales and via various administrative or jurisdictional authorities. For example, land use—and thus the amount of forest land—can be influenced by federal, state, and local policies, which all carry their own costs borne by the entities that enforce those policies. Similarly, how forests are managed can be influenced by local, regional, and international market forces. Although a full accounting of the costs and benefits of any given policy change to increase stored carbon necessarily would focus on the costs of implementing a policy change and expected incremental gains in stored carbon, it is important to remember that current levels of stored carbon are had in the present at least partly because of past investments in various policies and programs that have incentivized landowners to retain land in forest and to manage that land in a particular way.

Sources of Uncertainty

Forest Carbon Estimates

There are several uncertainties associated with our forest carbon projections that are common to all similar studies, including sample error, measurement error, modeling error, and error in the future state of land use changes and other conditions (Coulston et al. 2015). Because the inventory data are sample-based, each estimated component (e.g., forest carbon density by age class) has a standard error. Westfall and Patterson (2007) found that measurement error of changes in tree volume was approximately four percent of sampling error. Tree volume change is highly correlated with carbon stock change in the live tree carbon pool. The combined uncertainty of the historical forest carbon stock change (sequestration) estimates, developed using Monte Carlo analysis, is about ±17 percent

(EPA 2014). However, uncertainty approaches ± 40 percent using error propagation techniques, suggesting that uncertainty in the inventory is somewhat dependent on the assessment method. Our projected change in carbon stock encompasses the previously mentioned uncertainties, but has additional modeling uncertainty and error in the future state. Error in the future state includes error arising from, for example, unknowable future land use changes, potential CO_2 and N fertilization effects on C accumulation rates by age class, and changes in temperature and precipitation patterns. Further, our projection approach relies on an age transition matrix arising from field observations of disturbance, cutting, and normal mortality rates. There can be significant temporal variability in the amount and types of forest cutting (e.g., clearcutting, partial cutting) and in the amount and severity of disturbances, which suggests that there could be significant variability in the age transition matrix.

Social Cost of Carbon

Discount rates affect our results through two channels. First, it is a particularly important SCC parameter, because the SCC is essentially an estimated present value of the future damages of climate change at the time a ton of CO_2 is emitted. Second, we estimate the effect of carbon sequestration over the coming several decades. The rates chosen to discount values from the time of sequestration back to 2016 also have very important effects on our estimates.

Analysts differ in their thinking about which factors should be included in discount rates that are intended to be used for long-term investments in societal well-being (Cropper 2013). Federal agencies, in consultation with the U.S. Office of Management and Budget, develop recommended discount rates for federal analysts to use. However, it is recognized that standard discount rates may be inappropriate for use in projects that generate intergenerational effects. As such, there is no universally accepted set of discount rates, analysts (e.g., the U.S. Interagency Working Group 2010; 2013; 2015) often conduct sensitivity analysis to illuminate the influence of the discount rate.

As discussed by many authors (e.g., Arrow et al. 2014), uncertainties about the future affect discount rates and make them, as well, uncertain. As shown by Weitzman (2001) and many others, when key aspects of the future (e.g., output and consumption) are uncertain, lower discount rates should be applied to benefits and costs that occur farther into the future. For example, Weitzman suggests that the immediate future (one to five years) should be discounted at four percent per year, 6 to 25 years at three percent, 26 to 75 years at two percent, 76 to 300 years at one percent and over 300 years at 0 percent. These findings are not incorporated into the Interagency Working Group analysis, but as discussed in Arrow et al. (2014), the French and British governments apply lower discount rates to benefits and costs that occur farther in the future.

Also, an additional, and particularly important, type of uncertainty related to climate change is uncertainty regarding climate-induced catastrophe. Climate change is expected to create the types of damages in the U.S. discussed in Rhodium Group (2014), but how large will they be? How likely are extreme damages that significantly affect future welfare? There is, of course, significant uncertainty regarding such extreme effects, but hedge investments like carbon sequestration can reduce the chance of catastrophes.

Healthy forests often enhance and support ecosystem services (e.g., water quality and biodiversity) that are endangered by climate change and help mitigate extreme downside risk. As Weitzman (2013) discusses, if investments like carbon sequestration mitigate large downside risks, this also reduces the discount rate(s) that should be applied and increases the social cost of carbon. As possible in the three IAMs employed, the Interagency Working Group included aspects of extreme risk in its SCC estimates. Fully incorporating risk, and especially risk of catastrophe, in such models is very challenging, however, especially when analyzing forests, which likely reduce those risks.

Voluntary Incentives and Adoption

Two of the scenarios include afforesting 30 million acres in the eastern U.S., which would largely be achieved by providing incentives to private landowners. The USDA has five voluntary incentive programs, which account for over 95 percent of USDA conservation spending (Claassen, 2014). When estimating benefits, the possibility of incentive-related problems would need to be considered (Claassen et al. 2008).

First, it is possible, in practice, that carbon estimated to be sequestered by voluntary incentive programs may not be fully additional. The USDA is unable to observe what would have happened had a given incentive program not been implemented, so it is possible that some of the resulting gains in carbon would have been sequestered without the program. For example, landowners concerned about climate change may enroll in USDA conservation programs to get credit for steps they would have taken without such programs (Duke et al. 2013). Lubowski et al. (2003) estimate that about 10 percent of land enrolled in the Conservation Reserve Program between 1982 and 1997 would have been taken out of agricultural production anyway, due to market factors.

Second, slippage (or leakage) also can occur. For example, although steps are taken to avoid landowners “gaming” USDA incentive programs (Claassen et al. 2008), landowners may sometimes bring land into production that was previously unfarmed to compensate for land enrolled in a USDA voluntary conservation incentive program. Wu (2000) found that in the central U.S., such slippage offset between nine and 14 percent of erosion control benefits resulting from the Conservation Reserve Program. Lubowski et al. (2003) estimated that the Conservation Reserve Program reduced unenrolled forested area by about 200,000 acres, or approximately 15 percent of the measured impact on forests. Despite these leakage effects, carbon-positive externalities also accrue from USDA conservation policies and programs targeted toward other ecosystem services. For example, landowners interested in retiring land may participate in the Wetlands Reserve Enhancement Program (WREP), which will likely generate carbon benefits. Incorporating carbon-specific criteria in project selection may help moderate slippage while improving multi-benefit returns on program investments.

CONCLUSION

We found that existing data and analysis permit the development of national-level estimates of stored carbon and its value in response to hypothetical land use and forest disturbance policy scenarios. Continued support of the USDA Forest Service's Forest Inventory and Analysis Program, which develops and maintains data critical for making national-level carbon estimates and projections, is warranted, as is support for research and development efforts aimed at improving data development, including refining estimates of the per-ton value of carbon. Building and improving on these data will also help refine regional estimates of carbon sequestration. Improvements in the ability to evaluate regional differences in per ton and per acre values of carbon, including the nature of sequestration over time for different management regimes, will allow for more specific policy recommendations.

Our estimates of stored carbon likely to result from the various policy scenarios examined suggest that the greatest carbon gains would be obtained from (in order of largest impact on stored carbon): 1) afforestation and reforestation policies, 2) reducing forest conversion due to development, and 3) reducing wildfire. Given that such policies have long played a role in USDA conservation efforts, they would seem to be a viable approach, should the USDA choose to pursue opportunities for increasing stored carbon in the U.S. Such policies might be implemented by offering financial incentives to private landowners to plant trees, and emphasizing the restoration of existing forests. It should be noted that if policy costs were included, these priorities might change. A full cost-benefit analysis would provide more complete information for supporting policy choices.

Although afforestation and restoration policies may be viable approaches for increasing stored carbon, analyses of the degree to which landowners might respond to any afforestation or restoration incentives, including analysis of potential slippage, are somewhat limited. To understand the potential to achieve results, as reflected in these policy scenarios, would require social science research to improve understanding of the degree to which private landowners might respond to incentives of varying amounts, as well as whether some behavioral changes might be possible in the absence of financial incentives (via outreach and technical assistance, for example).

References

Arrow, K, M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, R. Pindyck, W. Pizer, P. Portney, T. Sterner, R. Tol and M. Weitzman. 2014. "Should Governments Use a Declining Discount Rate in Project Analysis?" *Review of Environmental Economics and Policy* 8(2):145–163.

Claassen, R, A. Cattaneo, and R. Johnson. 2008. "Cost-Effective Design of Agri-Environmental Payment Programs: U.S. Experience in Theory and Practice." *Ecological Economics* 65:737–752.

Claassen, R. 2014. "Conservation Spending Seeks to Improve Environmental Performance in Agriculture." Washington, D.C.: U.S. Department of Agriculture, http://www.ers.usda.gov/topics/natural-resources-environment/conservation-programs/background.aspx.

Claassen, R., L. Hansen, M. Peters, V. Breneman, M. Weinberg, A. Cattaneo, P. Feather, D.

Cropper, ML. 2013. "How Should Benefits and Costs Be Discounted in an Intergenerational Context?" *RFF Resources,* 183.

Duke, J, S. Dundas and K. Messer. 2013. "Cost-Effective Conservation Planning: Lessons from Economics." *Journal of Environmental Management* 125:126–133.

Ellenwood, M.S., L. Dilling, and J.B. Milford. 2012. "Managing United States Public Lands in Response to Climate Change: A View from the Ground Up." *Environmental Management* 49(5):954–967.

Englin, J. and J.M. Callaway. 1995. "Environmental Impacts of Sequestering Carbon through Forestation." *Climate Change* 31:67–78.

Gadsby, D. Hellerstein, J. Hopkins, P. Johnston, M. Morehart, and M. Smith. 2001. "Agri-Environmental Policy at the Crossroads: Guideposts on a Changing Landscape." *Agricultural Economic Report* No. 794. Washington, D.C.: U.S. Department of Agriculture, Economic Research Service.

Greenstone, M., E. Kopits, and A. Wolverton. 2013. "Developing a Social Cost of Carbon for U.S. Regulatory Analysis: A Methodology and Interpretation." *Review of Environmental Economics and Policy* 7(1):23–46. doi:10.1093/reep/res015

Hope, C., J. Anderson and P. Wenman. 1993. "Policy Analysis of the Greenhouse Effect: An Application of the PAGE Model." *Energy Policy* 21(3):327–338.

Kline, J.D., M.E. Harmon, T.A. Spies, A.T. Morzillo, R.J. Pabst, B.C. McComb, F. Schnekenburger, K.A. Olsen, B. Csuti, and J.C. Vogeler. 2016. "Evaluating Carbon Storage, Timber Harvest, and Habitat Possibilities for a Western Cascades (USA) Forest Landscape." *Ecological Applications* Volume 26, Issue 7, Pages 2044–2059.

Lewandrowski, J., M. Peters, C. Jones, R. House, M. Sperow, M. Eve, and K. Paustian. 2004. "Economics of Sequestering Carbon in the U.S. Agricultural Sector." *Technical Bulletin* No. 1909. Washington, D.C.: U.S. Department of Agriculture, Economic Research Service.

Lubowski, R, A. Plantinga and R. Stavins. 2003. "Determinants of Land-Use Change in the United States, 1982–1997." Discussion Paper 03–47. Washington, D.C.: Resources for the Future.

McKinley, D.C., M.G. Ryan, R.A. Birdsey, C.P. Giardina, M.E. Harmon, L.S. Heath, R.A. Houghton, R.B. Jackson, J.F. Morrison, B.C. Murray, D.E. Pataki, and K.E. Skog. 2011. "A Synthesis of Current Knowledge on Forests and Carbon Storage in the United States." *Ecological Applications* 21(6):1902–1924.

McLaughlin, G. 2013. "Assessing the Potential Impacts of Forest Management Practices on Wildlife Habitat, Carbon Sequestration, and Timber Harvesting in Coastal British Columbia." Thesis. Vancouver, British Columbia: University of British Columbia.

Mishan, E.J. and E. Quah. 2007. *Cost-Benefit Analysis,* 5th ed. New York, NY: Routledge.

Nordhaus, W. 1992. "An Optimal Path for Controlling Greenhouse Gases." *Science* 258:1315–1319.

O'Connell, B. M. et al. 2014. "The Forest Inventory and Analysis Database: Database Description and User Guide Version 6.0.1 for Phase 2. Washington, D.C.: U.S. Department of Agriculture, Forest Service, http://www.fia.fs.fed.us/library/database-documentation/.

Plantinga, A.J. and J. Wu. 2003. "Co-Benefits from Carbon Sequestration in Forests: Evaluating Reductions in Agricultural Externalities from an Afforestation Policy in Wisconsin." *Land Economics* 79:74–85.

Rodium Group. 2014. "American Climate Prospectus: Economic Risks in the United States." Prepared as an input to the Risky Business Project. New York, NY: http://climateprospectus.org/assets/publications/AmericanClimateProspectus_v1.2.pdf.

Schwenk, W.S., T.M. Donovan, W.S. Keeton, and J.S. Nunery. 2012. "Carbon Storage, Timber Production, and Biodiversity: Comparing Ecosystem Services with Multi-Criteria Decision Analysis." *Ecological Applications* 22:1612–1627.

Seidl, R., W. Rammer, D. Jager, W.S. Currie, and M. J. Lexer. 2007. "Assessing Trade-Offs Between Carbon Sequestration and Timber Production Within a Framework of Multi-Purpose Forestry in Austria." *Forest Ecology and Management* 248:64–79.

Smith, S. and N. A. Braathen. 2015. “Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues.” *OECD Environment Working Papers*, No. 92, Paris: OECD Publishing, http://dx.doi.org/10.1787/5jrs8st3ngvh-en.

Tol, R. 1999. “The Marginal Costs of Greenhouse Gases.” *The Energy Journal* 20(1):61–81.

U.S. Department of Agriculture, Forest Service. 2012. “National Forest System Land Management.” *Federal Register* 77(68):21162–21276.

U.S. Department of Agriculture. 2014. “Strategic Plan: Fiscal Years 2014–2018.” Washington, D.C.: Office of Chief Financial Officer, U.S. Department of Agriculture.

U.S. Department of Agriculture. 2016. “Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals: 2015 to 2060.” Washington, D.C.: U.S. Department of Agriculture, https://www.usda.gov/oce/climate_change/mitigation_technologies/Projections2015documentation01192016.docx.

U.S. Department of State. 2015. “2016 Second Biennial Report of the United States of America, Under the United Nations Framework Convention on Climate Change.” Washington, D.C.: State Department.

U.S. Environmental Protection Agency. 2015. “Fact Sheet: Social Cost of Carbon.” Washington, D.C.: Environmental Protection Agency, https://www3.epa.gov/climatechange/Downloads/EPAactivities/social-cost-carbon.pdf.

U.S. Forest Service. 2016. “Forest Inventory and Analysis: Fiscal Year 2015 Business Report.” Washington, D.C.: U.S. Forest Service, http://www.fia.fs.fed.us/library/bus-org-documents/docs/FIA_Annual_Report_2015_final.pdf.

U.S. Interagency Working Group on Social Cost of Carbon. 2010. “Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.” Washington, D.C.: Interagency Working Group on Social Cost of Carbon, http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

U.S. Interagency Working Group on Social Cost of Carbon. 2013 (revised 2015). “Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.” Washington, D.C.: Interagency Working Group on Social Cost of Carbon, https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.

U.S. Interagency Working Group on Social Cost of Carbon. 2013. “Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.” Washington, D.C.: Interagency Working Group on Social Cost of Carbon, https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

Wear, D.N. and J.W. Coulston. 2015. “From Sink to Source: Regional Variation in U.S. Forest Carbon Futures.” *Scientific Reports* 5, art. no. 16518.

Weitzman, M. 2001. “Gamma Discounting.” *The American Economic Review* 91(1):260–271.

Weitzman, M. 2013. “Tail-Hedge Discounting and the Social Cost of Carbon.” *Journal of Economic Literature* 51(3):873–882.

Wu, J.J. 2000. “Slippage Effects of the Conservation Reserve Program.” *American Journal of Agricultural Economics* 82(4):979–992.

This page was intentionally left blank.