

# Climate Change and Ecosystem Services: The Contribution of and Impacts on Federal Public Lands in the United States

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**Abstract**—The Intergovernmental Panel on Climate Change (IPCC) (2007) reports a likely 2 °C to 4.5 °C temperature rise in the upcoming decades. This warming is likely to affect ecosystems and their ability to provide services that benefit human well-being. Ecosystem services valuation (ESV), meanwhile, has emerged as a way to recognize the economic value embodied in these services that is not currently reflected in markets. To contribute to better understanding of how U.S. conservation lands may be affected by climate change, we outline a method and preliminary estimates of the value of ecosystem services harbored or produced in abundance on those lands as well as how that value may change under climate change scenarios. We combine GIS analysis with the benefits transfer method to estimate potential global-warming-induced changes in the economic value of ecosystem services produced by U.S. conservation lands. Using conservative assumptions, the overall trend indicates that the majority of ecosystem services values decreases as temperature increases. While some ecosystem service values increase in the 2 °C scenario in several regions, the values markedly decrease in all but one region under the 4.5 °C scenario. These results are consistent with other major studies, such as the IPCC and the Cost of Policy Inaction reports, and indicate the important role of public conservation lands in providing ecosystem services and the need for policy action to avoid major economic losses were climate change to impair the health of those lands.

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## Introduction

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The importance and contribution of healthy ecosystems to human well-being has gained increasing awareness and attention in recent years. Ecosystems are defined as “a dynamic complex of plant, animal, and microorganism communities and the nonliving environmental interaction as a functional unit” (MEA 2005). The components of ecosystems, such as soil and trees, interact in complex processes that create functions that produce environmental goods and services. Ecosystem services are the benefits that people obtain, directly and indirectly, from ecosystems. There are various types of ecosystem services, including provisioning services, such as food, water and timber; regulating services that influence climate, water quality, floods and diseases; supporting services, including soil formation, photosynthesis and nutrient cycling; and cultural services that provide recreational, spiritual and aesthetic benefits (MEA 2005). See table 1 for descriptions and examples of ecosystem services.

The Millennium Ecosystem Assessment (MEA), a comprehensive work of over 1500 scientists from across the globe, provides a global, integrated evaluation of the current changes and consequences occurring in ecosystems. Intended for use by decision makers and the public, the assessment highlights the vital role of ecosystems as they “contribute to human well-being and poverty alleviation” (MEA 2005). However, despite the wide-scale acknowledgement that ecosystems are fundamental to Earth’s life-support systems and vital to human welfare, the majority of the benefits yielded by ecosystem services are currently not accounted for in the economic system. As a partial result, their value is not equally weighted in decisions that directly impact their functioning and well-being (Costanza and others 1997; Straton 2006; Turner and others 2003).

For example, healthy forests slow water runoff and, when combined with sufficient flood plains, they protect against flooding. When forest cover is lost and flood plains are filled, flooding downstream is increased. If natural flood prevention functions (previously provided for free) are destroyed or diminished, then flood damage will exact costs on individuals and communities. Private individuals, firms, and governments will either suffer the costs of flood damage or they will have to pay for engineering structures and storm water infrastructure to compensate for the loss of ecosystem flood prevention. Without healthy ecosystems, taxpayers, businesses, and governments incur damage or costs to repair or replace these ecosystem services.

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Watson, Alan; Murrieta-Saldivar, Joaquin; McBride, Brooke, comps. 2011. Science and stewardship to protect and sustain wilderness values: Ninth World Wilderness Congress symposium; November 6-13, 2009; Meridá, Yucatán, Mexico. Proceedings RMRS-P-64. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 225 p.

**Table 1**—Ecosystem functions, processes and services<sup>a</sup>.

<b>Functions</b>	<b>Ecosystem Infrastructure and Processes</b>	<b>Goods and Services (Examples)</b>
<b><i>Regulating Services</i></b>		
Biological control	Population control through trophic-dynamic relations	Provides pest and disease control, reduces crop damage
Climate regulation	Influence of land cover and biologically mediated processes on climate	Maintenance of a favorable climate promotes human health, crop productivity, recreation, and other services
Disturbance prevention	Influence of ecosystem structure on dampening environmental disturbances	Prevents and mitigates natural hazards and natural events, generally associated with storms and other severe weather
Gas regulation	Role of ecosystems in biogeochemical cycles	Provides clean, breathable air, disease prevention, and a habitable planet
Pollination	Role of biota in movement of floral gametes	Pollination of wild plant species and harvested crops
Soil retention	Role of vegetation root matrix and soil biota in soil retention	Maintains arable land and prevents damage from erosion, and promotes agricultural productivity
Waste treatment	Role of vegetation and biota in removal or breakdown of nutrients and compounds	Pollution control/detoxification, filtering of dust particles through canopy services
Water regulation	Role of land cover in regulating runoff and river discharge	Provides natural irrigation, drainage, channel flow regulation, and navigable transport
<b><i>Supporting Services</i></b>		
Navigational services	Variety in nature with navigational value	Use of bodies of water, land and natural objects for movement, travel, trade, etc.
Nutrient regulation	Role of biota in storage and recycling of nutrients	Promotes health and productive soils, and gas, climate and water regulations
Soil formation	Weathering of rock, accumulation of organic matter	Promotes agricultural productivity, and the integrity of natural ecosystems
<b><i>Provisioning Services</i></b>		
Food	Conversion of solar energy into edible plants and animals	Hunting, gathering of fish, game, fruits etc.; small scale subsistence farming and aquaculture
Genetic resources	Genetic material and evolution in wild plants and animals	Improve crop resistance to pathogens and pests
Medicinal resources	Variety in (bio)chemical substances in, and other medicinal uses of, natural biota	Drugs, pharmaceuticals, chemical models, tools, test and assay organisms
Nursery function	Suitable reproduction habitat	Maintenance of commercially harvested species
Raw materials	Conversion of solar energy into biomass for human construction and other uses	Building and manufacturing, fuel and energy, fodder and fertilizer
Refugium function	Suitable living space for wild plants and animals	Maintenance of biological and genetic diversity (and thus the basis for most other functions)
Water supply	Filtering, retention, and storage of fresh water (e.g. in aquifers and snow pack)	Provision of water for consumptive use, includes both quality and quantity
<b><i>Cultural Services</i></b>		
Aesthetic information	Attractive landscape features	Enjoyment of scenery
Cultural and artistic information	Variety in natural features with cultural and artistic value	Use of nature as motive in books, film, painting, folklore, national symbols, architecture, advertising etc.
Ornamental resources	Variety of biota in natural ecosystems with (potential) ornamental use	Resources for fashion, handicraft, jewelry, pets, worship, decoration and souvenirs
Recreation	Variety in landscapes with (potential) recreational uses	Travel to natural ecosystems for ecotourism, outdoor sports etc.
Science and education	Variety in nature with scientific and educational value	Use of natural systems for school excursions, etc. Use of nature for scientific research.
Spiritual and historic information	Variety in natural features with spiritual and historic value	Use of nature for religious or historic purposes (i.e., heritage value of natural ecosystems and features)

<sup>a</sup>After de Groot, et al. 2002.

## Ecosystem Services Valuation

In a 1997 seminal work, Costanza and others (1997) argue that ecosystem services should be embodied within the complete economic worth of the Earth, and estimated that 17 ecosystem services produced or supported by 16 biomes are worth, on average, \$33 trillion annually, with most of this value accruing outside traditional markets. For comparison, global GNP was approximately \$18 trillion. Ecosystem Services Valuation (ESV) has since emerged as an ecological-economic approach to identifying and valuing the functions, goods, and services produced by ecosystems that benefit human populations but that are not currently traded, and therefore ascribed value, in markets (Costanza and others 1997). The approach is increasingly gaining recognition as a way to integrate the value of natural systems into an otherwise incomplete set of analyses and decision making processes (Foster and Gough 2005; Straton 2006). ESV attempts to capture the aspects of ecological impact that have previously gone unacknowledged in frameworks of costs and benefits that are used in development, land use, and other projects. Successful projects, such as the Payment for Ecosystem Services program currently being conducted on a national level in Costa Rica, highlight ESV as a valid and more complete approach to decision making on the basis that human well-being is entirely dependent on healthy ecosystems, for which there is no absolute substitution (May and others 2002; Pagiola 2002).

## Climate Change and Federal Public Lands in the United States

ESV can contribute to better understanding of the potential costs of climate change and, therefore, can inform climate change mitigation and adaptation measures. Perhaps chief among these measures are policies and actions affecting how we manage public conservation lands where many ecosystem

services are harbored or produced in abundance. Therefore, in this study we apply ESV to examine the current contribution of U.S. public lands to ecosystem services value and the potential change in that value due to climate change.

## Methods

We estimated the value of ecosystem services using a refined “benefits transfer method.” Benefits transfer is a way to estimate economic value for ecosystem services by transferring available information from studies already completed in one location and/or context to the area or context in question. In our refined version we calibrated every input as much as possible with specific information for our study. The overall process consists of four steps:

1. Allocate the U.S. Public Lands (defined as the land under the stewardship of the Forest Service, National Park Service, Fish and Wildlife Service, and Bureau of Land Management)—approximately 275 million hectares (ha) in all—to eight biomes (Open Water, Rock and Ice, Urban, Forest, Shrub/ Scrub, Grassland, Crops and Wetlands).

2. Establish indicators of baseline ecosystem health and baseline productivity for 24 ecosystem services (see table 1 for a list and description of these services).

3. Ascertain changes in biome health / ecosystem service productivity under two temperature change scenarios: +2 °C and +4.5 °C.

4. Apply dollar-value estimates of the value of the ecosystem services per hectare and multiply hectares by productivity (baseline and scenarios), and by dollars to generate estimates of total ecosystem service value.

These steps, described in more detail below, were repeated for each of fifteen large bioregions, for which we used National Land Cover Database “zones” as proxies (Multi-Resolution Land Characteristics Consortium (MRLC) 2008) (fig. 1).

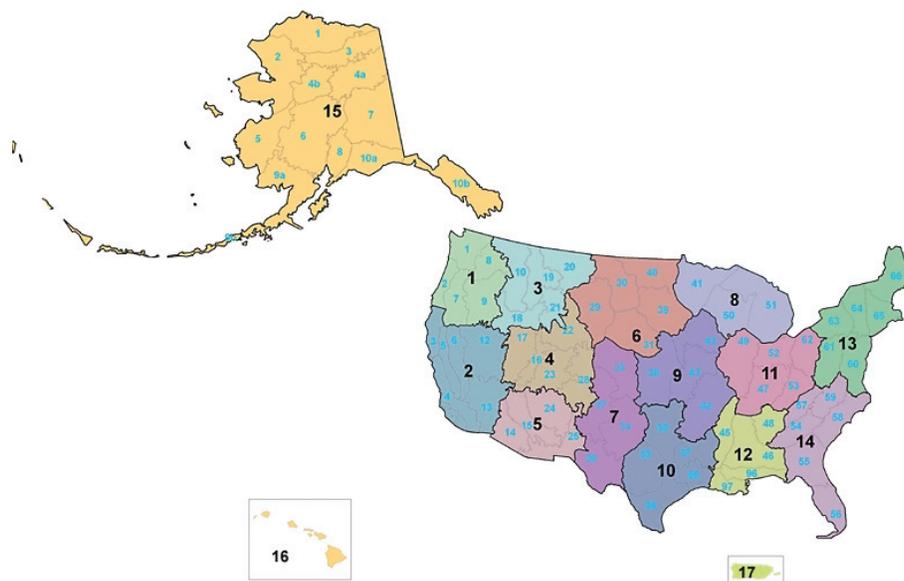


Figure 1—National land cover database zones (ecoregions) (MRLC 2008).

Allocation of U.S. Public Lands (Federal lands) to biomes was accomplished by overlaying the National Land Cover Dataset with a Federal lands layer. We retained attributes of each 30 m<sup>2</sup> (0.09 ha) grid cell to enable later identification of each cell according to the agency responsible for its management and whether it was designated wilderness.<sup>1</sup> The result was a map of the U.S. Federal lands classified by land cover type (21 classes), management agency (4 classes) and wilderness (yes/no). We then assigned each cell to one

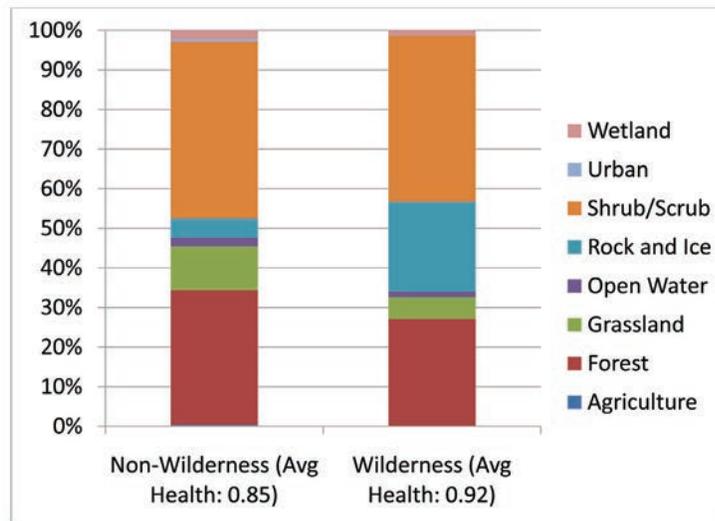
or more of eight biomes: Open Water, Rock and Ice, Urban, Forest, Shrub and Scrub, Grasslands, Crops/Agriculture, and Wetlands.

For most land cover types, all hectares represented by the cells were assigned to one biome (table 2). The exceptions were Woody Wetlands, which was divided 50:50 among Forest and Wetlands biomes; and Herbaceous Wetlands, which was divided 50:50 among Grassland and Wetlands. Figure 2 depicts the resulting distribution of Federal wilderness and non-wilderness lands among these eight biomes. Wilderness has relatively more rock and ice, and less forest, grassland and shrub/scrub than non-wilderness lands.

<sup>1</sup> Due to the size of the Alaska (NLCD zone 15) data set, we used a 990 m<sup>2</sup> (approximately 98 ha) grid cell size.

**Table 2**—Allocation of land cover to biome.

NLCD Value	Land cover type	Biome							
		Open water	Rock and Ice	Urban	Forest	Shrub/ Scrub	Grass land	Crops	Wet lands
11	Open Water	1.00	-	-	-	-	-	-	-
12	Perennial Ice/Snow	-	1.00	-	-	-	-	-	-
21	Developed, Open Space	-	-	1.00	-	-	-	-	-
22	Developed, Low Intensity	-	-	1.00	-	-	-	-	-
23	Developed, Medium Intensity	-	-	1.00	-	-	-	-	-
24	Developed, High Intensity	-	-	1.00	-	-	-	-	-
31	Barren Land	-	1.00	-	-	-	-	-	-
32	Unconsolidated Shore	-	1.00	-	-	-	-	-	-
41	Deciduous Forest	-	-	-	1.00	-	-	-	-
42	Evergreen Forest	-	-	-	1.00	-	-	-	-
43	Mixed Forest	-	-	-	1.00	-	-	-	-
51	Dwarf Shrub (AK Only)	-	-	-	-	1.00	-	-	-
52	Shrub/Scrub	-	-	-	-	1.00	-	-	-
71	Grassland/Herbaceous	-	-	-	-	-	1.00	-	-
72	Sedge/Herbaceous (AK Only)	-	-	-	-	-	1.00	-	-
73	Lichens (AK Only)	-	-	-	-	1.00	-	-	-
74	Moss (AK Only)	-	-	-	-	1.00	-	-	-
81	Pasture/Hay	-	-	-	-	-	1.00	-	-
82	Cultivated Crops	-	-	-	-	-	-	1.00	-
90	Woody Wetlands	-	-	-	0.50	-	-	-	0.50
95	Emergent Herbaceous Wetlands	-	-	-	-	-	0.50	-	0.50



**Figure 2**—Distribution of federal wilderness and non-wilderness lands among biomes.

Next, ecosystem health and baseline ecosystem service productivity were established for each cell. We developed a proxy for ecosystem health based on a subset of the “indicators of wildness” previously used to identify the areas of the United States that are most wild (Aplet and others 2000). Using the methods of Aplet and others we combined the relative “Solitude,” “Remoteness,” and “Lack of Pollution” for the same 30-m cells used to assign land cover to biome.<sup>2</sup> These indicators served as reasonable proxies for the degree to which a given piece of land was free from anthropogenic influences that could degrade ecosystem function. Each indicator was measured on a 1-to-5 scale, which, when summed, produced a combined score between 3 and 15. Dividing each score by the maximum possible (15) produced an indicator of ecosystem health on a 0-to-1 scale. These health indicators were unique for each combination of ecoregion (zone), land cover type, biome, management agency and wilderness status. As noted in figure 2, the average health for areas within designated wilderness was slightly higher than for areas outside. Average health for each zone-biome combination is presented in table 3.

<sup>2</sup>Aplet et al. (2000) also use “Natural Composition,” “Unaltered Structure,” and “Uncontrolled Processes” to indicate wildness. We did not employ these here, each for its own reason. The authors measured Natural Composition using the same land cover data by which we assigned areas to biomes, thus the Natural Composition indicator did not add to our model. The measure for Unaltered Structure is the location of cities, roads and other infrastructure, and would serve much the same purpose as the Solitude and Remoteness indicators that we used—that is the impact of the presence of people and the primary infrastructure that connects them (roads)—as a proxy for decreases in ecosystem health. Finally, Uncontrolled Process was indicated by a lack of dams, and without additional indicators of the extent and location of fire suppression or other means by which humans control natural processes across many or at least more biomes, we were concerned that including Uncontrolled Process would bias our model and its results toward those ecosystem services produced or delivered by waterways.

Baseline ecosystem service productivity by biome was extracted or, in some cases, interpolated from Costanza and others (1997). These figures indicate the relative effectiveness of the various biomes for generating or harboring each of 24 ecosystem services. So, for example, Forests scored a 1 for the ecosystem service of climate regulation, meaning forests do as well as any biome could to regulate climate. The Shrub/Scrub biome, by contrast, only scored 0.8.

These biome-ecosystem service productivity ratios were then applied to each grid cell to produce an estimate of ecosystem service productivity for every combination of ecoregion (zone), land cover type, health, biome, management agency and wilderness status.

Because we were addressing federally managed lands, we made a further adjustment to our model to account for the fact that certain ecosystem service values would not be realized due to the protective nature of their management. Namely, because extractive activities are generally proscribed in wilderness areas, we set the productivity of designated wilderness to 0 for food and raw material production.

In step three, we employed results from the literature to adjust the baseline ecosystem health indicator to reflect possible changes in ecosystem service productivity for each biome/ecosystem service combination for two warming scenarios: a 2 °C and a 4.5 °C temperature increase. For example, the IPCC (2007) predicts that climate change will likely increase forest sensitivity to disturbances in both low and high warming scenarios, decreasing the productivity of regulating services. This reduction is anticipated to stem from increased flood occurrences as well as a potential invasion from the Southern beetle migrating north due to warmer temperatures. Thus, in the 2 and 4.5 °C scenarios, based on IPCC predictions, the new figures reflect declines in ecosystem productivity. Estimates were based on the degree of certainty of the IPCC predictions (usually low, medium, or high). The change in productivity is expressed as a percentage change from the baseline, or current conditions.

**Table 3**—Average health (weighted by area), by zone and biome.

Zone Name	Agriculture	Forest	Grassland	Open Water	Rock and Ice	Shrub/Scrub	Urban	Wetland
	----- Percent -----							
Alaska	64.98	93.85	95.81	94.84	94.54	96.14	73.47	94.79
Central & Southern West Coast	59.11	81.11	79.07	70.60	82.94	83.86	62.08	66.71
Central Midwest	56.77	67.07	63.48	55.03	70.39	66.74	63.80	55.59
Central Rockies	77.40	79.25	81.97	77.98	85.06	84.32	71.32	80.11
Great lakes	62.09	76.23	67.24	74.21	59.92	76.55	63.26	73.39
Midwest	54.34	55.56	53.24	52.16	55.60	55.34	51.86	52.42
New England & Mid-Atlantic	48.83	58.69	54.91	53.10	59.97	57.79	52.22	52.36
Northern Plains	80.25	76.77	84.47	78.70	80.25	84.37	74.59	80.75
Northern Rockies	77.87	84.76	87.19	80.85	86.92	86.26	71.41	85.03
Pacific Northwest	67.68	79.38	84.57	74.47	85.57	90.48	71.72	80.41
Southeast	54.30	56.84	60.03	64.76	53.07	55.52	49.60	69.03
Southwest	58.50	80.13	79.86	73.09	85.16	77.37	60.07	69.39
West Texas & Southern Plains	83.44	72.33	84.63	78.35	86.51	87.58	74.87	76.44
Western Gulf	66.74	63.24	61.87	67.38	73.42	66.25	59.12	69.30

Finally (step four), we extracted a range of minimum and maximum dollar values per hectare for the 24 ecosystem services from current literature. The Millennium Ecosystem Assessment (2005), IPCC: North America (2007), Field and others (2007), and the *Cost of Policy Inaction: The case of not meeting the 2010 biodiversity target* (Braat and ten Brink 2008) are our primary data sources. Values were also updated from the Costanza and others (1997) paper to 2009 dollars using the Consumer Price Index. In the interest of producing only the most conservative possible estimates, we used only the lower end of the range of dollar-per-hectare estimates.

Multiplying hectares per biome (from step one) by ecosystem service productivity per biome and then ecosystem service value per hectare yielded an estimate of the total value for each ecosystem service in each NLCD zone.

We repeated the baseline ecosystem service value calculation using the percentage change in productivity (from step four) to adjust baseline productivity, so, our formula becomes:

$$\begin{aligned} & \text{hectares per biome (from step one)} \\ & \text{times } \textit{baseline} \text{ ecosystem service productivity per} \\ & \quad \text{biome and ecosystem service} \\ & \text{times percentage change in productivity for the warm-} \\ & \quad \text{ing scenarios} \\ & \text{times ecosystem service value per hectare.} \end{aligned}$$

This calculation was repeated for each ecoregion (NLCD) zone, biome, and ecosystem service for both the 2 °C and 4.5 °C scenarios to yield dollar-value estimates for each ecosystem

service for each scenario. Comparison of the results for each scenario yielded an estimate of the cost of inaction on climate change, at least as translated through the ecosystem service value of U.S. Federal conservation lands.

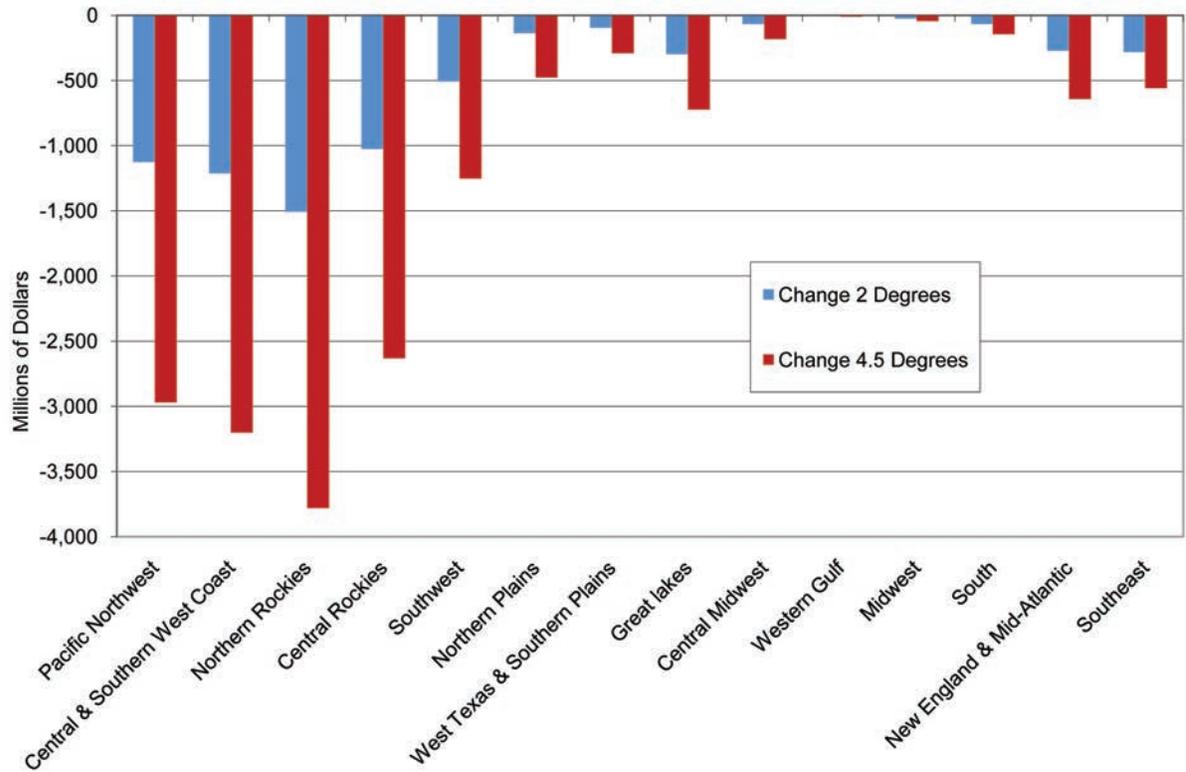
A sensitivity analysis was also performed to determine the percentage of the value of individual ecosystem services that contributed to the total value. This enabled a refined understanding of which inputs are most influential in the total value figures (see table 4 for an example of the sensitivity analysis for zone 1).

## Results and Discussion

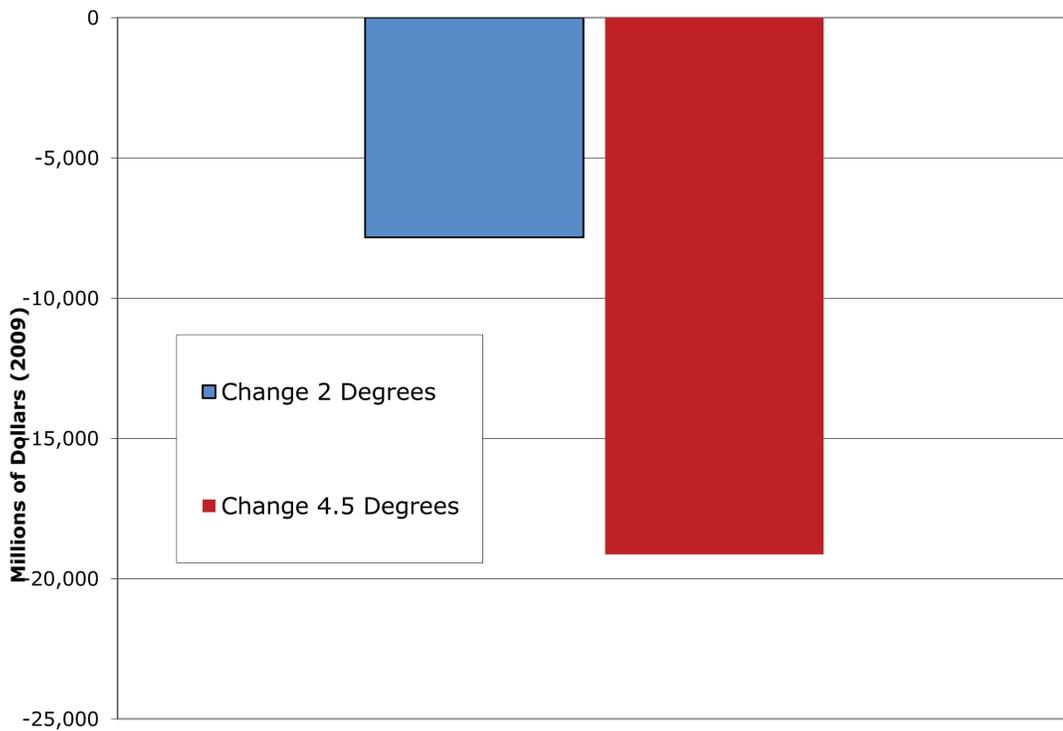
Using conservative estimates for the values, the overall trend indicates that the majority of ecosystem services values decrease as temperature increases. While value increased for several individual ecosystem services in the 2 °C warming scenario, overall ecosystem service value declined in all zones by a total of \$14.5 billion per year. In the 4.5 °C scenario, the value of all ecosystem services as well as overall value in each zone also declined, with total potential loss being \$36.1 billion (see figs. 3 and 4 and table 5 for a summary by bioregion; see fig. 5 and table 6 for a summary by ecosystem service). These results are consistent with other major studies such as the IPCC and the *Cost of Policy Inaction*. In addition, they indicate the important role of public conservation lands in providing ecosystem services and the need for policy action to avoid major economic losses were climate change to impair the health of those lands.

**Table 4**—Sample of the sensitivity analysis, for the 4.5 °C change scenario in Zone 1.

	Open Water	Rock & Ice	Urban	Forest	Shrub / Scrub	Grassland	Agriculture	Wetlands
	-----Percent-----							
Gas regulation	1	0	0	1	1	0	0	1
Climate regulation	27	29	0	41	32	11	0	55
Disturbance prevention	0	0	1	0	0	0	0	0
Water regulation	29	27	0	41	0	0	0	0
Water supply	0	0	0	0	0	0	0	0
Erosion control	0	0	0	0	0	0	0	0
Soil formation	0	0	0	0	0	0	0	0
Nutrient regulation	9	0	0	0	4	18	4	19
Waste treatment	2	0	0	0	0	1	0	8
Pollination	0	0	0	1	1	7	0	2
Biological control	0	0	0	0	0	1	0	0
Refugium function	1	1	0	1	0	1	0	1
Nursery function	0	0	0	0	0	0	0	0
Food	17	41	0	9	58	31	90	5
Raw materials	0	0	0	1	0	0	1	0
Genetic resources	0	0	0	1	0	0	0	1
Medical resources	0	0	0	0	0	0	0	0
Ornamental resources	0	0	0	1	0	1	0	0
Aesthetic information	0	1	1	0	0	2	0	1
Recreation	5	0	31	0	0	1	0	1
Cultural and artistic information	1	1	6	1	0	0	0	2
Spiritual and Historic information	0	0	0	0	0	0	0	0
Science and education	0	0	1	0	0	0	0	0
Navigational services	8	0	60	3	3	25	5	2
Total	100	100	100	100	100	100	100	100



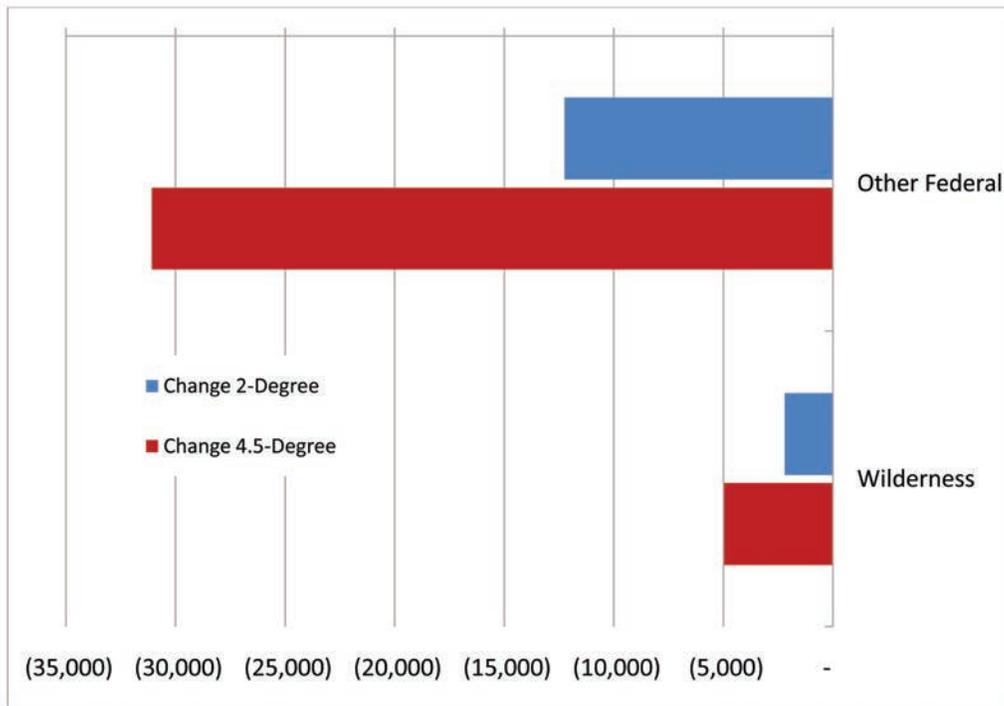
**Figure 3**—Change in ecosystem service value of U.S. Federal lands under 2 and 4.5 °C warming scenarios, conterminous United States, by region.



**Figure 4**—Change in ecosystem service value of U.S. Federal lands under 2 and 4.5 °C warming scenarios, Alaska.

**Table 5**—Ecosystem services value of U.S. Federal lands: baseline and under 2 and 4.5 °C warming scenarios, by region.

Region (NLCD Zone)	Baseline \$millions	Change 2 °C \$millions	Change 4.5 °C \$millions
Pacific Northwest	20,748	(1,125)	(2,970)
Central & Southern West Coast	32,414	(1,212)	(3,202)
Northern Rockies	25,426	(1,507)	(3,782)
Central Rockies	33,026	(1,026)	(2,632)
Southwest	14,879	(507)	(1,252)
Northern Plains	3,735	(138)	(477)
West Texas & Southern Plains	3,133	(95)	(292)
Great lakes	4,048	(298)	(723)
Central Midwest	2,169	(66)	(183)
Western Gulf	101	(5)	(9)
Midwest	1,230	(26)	(44)
South	1,173	(67)	(144)
New England & Mid-Atlantic	1,908	(272)	(643)
Southeast	3,215	(281)	(559)
Alaska	94,202	(7,827)	(19,132)
Total:	241,407	(14,452)	(36,044)



**Figure 5**—Change in ecosystem service value of U.S. Federal lands under 2 and 4.5 °C warming scenarios, by service.

**Table 6**—Ecosystem services value of U.S. Federal lands: baseline and under 2 and 4.5 °C warming scenarios, by service.

<b>Ecosystem Service</b>	<b>Baseline \$millions</b>	<b>Change 2 °C \$millions</b>	<b>Change 4.5 °C \$millions</b>
<b>Cultural</b>			
Aesthetic information	713	11	(82)
Cultural and artistic Information	1,438	10	(157)
Ornamental resources	565	8	(59)
Recreation	744	(15)	(64)
Science and education	209	(4)	(22)
Spiritual and historic information	125	1	(13)
<b>Provisioning</b>			
Food	79,697	(2,449)	(7,864)
Genetic resources	649	37	(54)
Medical resources	382	13	(34)
Nursery function	276	2	(29)
Raw materials	417	27	(34)
Refugium function	1,357	50	(128)
Water supply	40	(2)	(11)
<b>Regulating</b>			
Biological control	87	(6)	(12)
Climate regulation	90,238	(7,337)	(14,929)
Disturbance prevention	32	(2)	(6)
Erosion control	134	(12)	(25)
Gas regulation	1,256	(98)	(201)
Pollination	2,524	(183)	(370)
Waste treatment	1,063	(64)	(163)
Water regulation	42,528	(4,894)	(9,963)
<b>Supporting</b>			
Navigational services	8,822	358	(827)
Nutrient regulation	7,976	87	(990)
Soil formation	136	12	(8)
<b>Total</b>	<b>241,407</b>	<b>(14,450)</b>	<b>(36,045)</b>

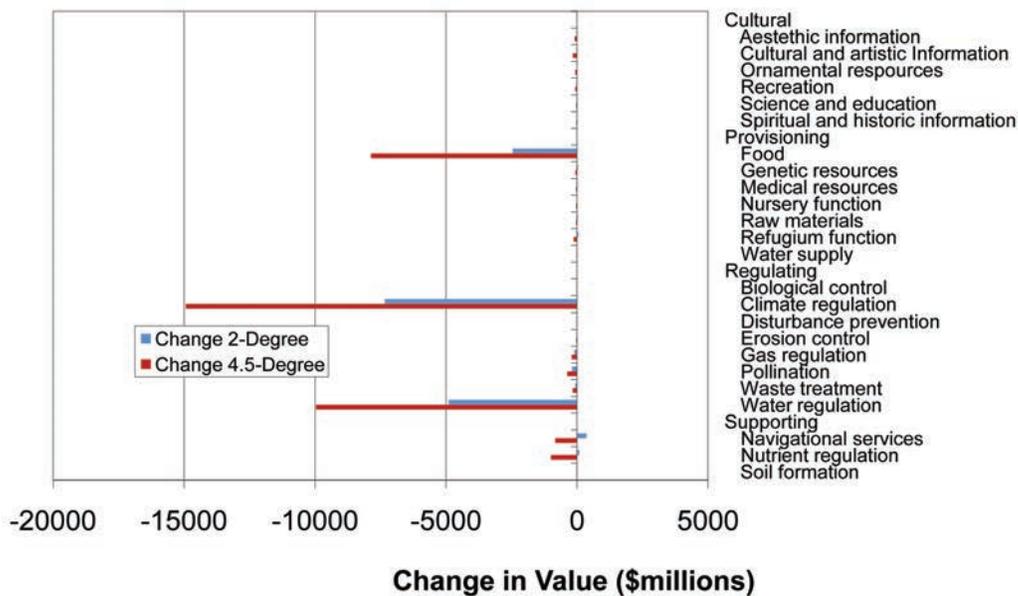
For those ecosystem services values that first gained (at 2 °C warming), then lost (at 4.5 °C), it is plausible that the functions tipped. Nutrient regulation and soil formation, for example, showed a substantial increase in value under the 2 °C scenario, as one might expect with warmer conditions and longer periods during which plants, microbes and other biota can effectively fix nutrients, break down leaf litter and other organic material, and build soil. But under the 4.5 °C scenario, that gain was reversed, perhaps as some other process already impaired by climate change—water supply, for example—limited nutrient cycling and soil formation capacity. Considering such interactions in a dynamic context, as opposed to the simple, static model presented here, would shed additional light on where and how such tipping points might operate.

One of the biggest factors behind regional differences in ecosystem service value (and its potential loss) from the Federal estate is obviously the size of the Federal estate in a given region. Alaska, for example, is in a class (and in a graph) by itself (fig. 4), and western regions generally have more Federal land and generally more total ecosystem service value at risk due to climate change. But other factors are important as well, especially the particular mix of biome and initial land health. Biome is important in the model because it is linked to the production of individual ecosystem services. Land health is important, because for

a given biome, the healthier the hectare, the higher the productivity. Regions with relatively more Federal land in forests—a biome with high potential productivity—or where more land is in a natural or undisturbed state provide more (and could lose more) ecosystem service value than would be indicated by Federal land area alone.

The same sort of phenomenon can play out as one considers the wilderness status of these areas. Designated wilderness represents just 15 percent of the Federal land included in this study. And, recall from figure 2 that relatively less designated wilderness is in forests, grasslands, and other highly productive areas. Thus, one might expect wilderness areas to produce disproportionately less ecosystem service value now and risk losing relatively less value under the climate change scenarios. The first of those assumptions appears to be true in that wilderness areas represent just 10.4 percent of baseline ecosystem service value of the Federal estate. This is due to the legal exclusion of the realization of some of the more valuable ecosystem services from wilderness areas, not because those values are not present.

The second result, however, is not evident, since wilderness areas could lose 8.8 and 19.8 percent of their value under the 2 and 4 °C climate change scenarios, respectively, while non-wilderness areas stand to lose just 5.7 and 14.4 percent of their ecosystem service value in those scenarios (see fig. 6). We infer that this is due to the greater relative



**Figure 6**—Change in ecosystem service value of U.S. Federal lands under 2 and 4.5 °C warming scenarios, for wilderness and non-wilderness lands.

health of wilderness areas at the outset, which produces a larger change in productivity due to climate change.

Clearly, action on climate change is necessary to ensure continued ecosystem services for and from all Federal lands (not to mention private, state, and other lands). Within the Federal estate, the results suggest that areas managed for their wilderness character are particularly important, both because they provide a model for healthy, productive ecosystems that more intensively managed lands might emulate, and because they could have more to lose from climate change.

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