Ecosystem carbon stocks and sequestration potential of federal lands across the conterminous United States

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Federal lands across the conterminous United States (CONUS) account for 23.5% of the CONUS terrestrial area but have received no systematic studies on their ecosystem carbon (C) dynamics and contribution to the national C budgets. The methodology for US Congress-mandated national biological C sequestration potential assessment was used to evaluate ecosystem C dynamics in CONUS federal lands at present and in the future under three Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) A1B, A2, and B1. The total ecosystem C stock was estimated as 11,613 Tg C in 2005 and projected to be 13,965 Tg C in 2050, an average increase of 19.4% from the baseline. The projected annual C sequestration rate (in kilograms of carbon per hectare per year) from 2006 to 2050 would be sinks of 620 and 228 for forests and grasslands, respectively, and C sources of 13 for shrublands. The federal lands' contribution to the national ecosystem C budget could decrease from 23.3% in 2005 to 20.8% in 2050. The C sequestration potential in the future depends not only on the footprint of individual ecosystems but also on each federal agency's land use and management. The results presented here update our current knowledge about the baseline ecosystem C stock and sequestration potential of federal lands, which would be useful for federal agencies to decide management practices to achieve the national greenhouse gas (GHG) mitigation goal.

biogeochemical modeling | ecosystem carbon dynamics | land use and land cover | federal lands | nonfederal lands

Federal lands were established to help sustain biodiversity, manage mineral and energy development, provide recreational opportunities, oversee timber harvesting, and protect these resources from human impacts (1). The US government has direct ownership of 2.63×10^6 km^2—nearly 30% of the whole national territory area. Clawson (2) stated, "Extensive federal land ownership has been an integral part of US society and economy throughout our national history." Natural resource use and deployment always involves the federal government to a greater extent on federal lands than on nonfederal lands.

The federal lands across the conterminous US (CONUS) account for about 23.5% of the CONUS terrestrial area. Their areal portion varies dramatically from state to state, ranging from 84.5% in Nevada to <2% in some eastern states, but more than 90% are concentrated in the western United States.

Numerous inventory- and modeling-based studies, using atmospheric (top-down) and ground-based (bottom-up) methods, have been conducted to quantify ecosystem carbon (C) stocks and changes in the United States. These studies agree on the presence of C sinks in the CONUS ecosystems (3). Changes in climate and land use exert profound effects on the ability of ecosystems to sequester atmospheric C and maintain a stable ecosystem C stock (3, 4). However, almost all studies focused on nonfederal lands or on a mixture of both private and federal lands; thus, no information about ecosystem C stock and dynamics is available for federal lands explicitly.

Recently, US Department of Interior (DOI) released "a strategy for improving the mitigation policies and practices of the Department of Interior" (5), which proposes principles and actions for developing an effective mitigation policy. Therefore, understanding the baseline ecosystem C stock and its change trend over time can be a fundamental reference for instituting federal agencies' mitigation policies and practices on greenhouse gas (GHG) emissions. Because of its large proportion in the CONUS territory and the advantage of federal government in policy making, federal lands can make a substantial contribution to national ecosystem C sequestration and GHG mitigation efforts.

The ecological constraints, combined with administrative and political constraints, make the attributes of federal lands differ from nonfederal lands, but few studies so far have focused on federal lands to reveal these differences and evaluate their effects on ecosystem C dynamics. As a result, few data are available from site observations for modeling validation and projections. This is a critical knowledge gap for national biological C sequestration potential assessment. Although some wall-to-wall studies could contain such information mixed with nonfederal lands, how much ecosystem C federal lands store and what their C sequestration potential could be in the future still remain unknown. This study evaluated ecosystem C dynamics in CONUS federal lands as related to land use, land management, and climate change under downscaled Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) A1B, A2, and B1 (6) (Table S1) at present and in the future.

Results

Ecosystem Dynamics of Federal Lands Under IPCC SRES Scenarios. Table 1 shows how the land use and land cover (LULC) (or ecosystem) could change from 2006 until 2050 under IPCC SRES scenarios A1B, A2, and B1. Generally, major changes would happen to forests (including mechanically disturbed forests),

Significance

There has been a critical knowledge gap for national biological C sequestration potential assessment due to a lack of relevant information about federal lands that cover nearly 30% of the whole US territory. Here, we present the results from a multimodel simulation approach and fill the current knowledge gap by revealing the C sequestration potential of federal lands across the conterminous United States and their contribution to the national ecosystem C budget through 2050. This kind of information can be a fundamental reference for federal agencies to develop long-term strategies for mitigating greenhouse gas (GHG) emissions and sustaining federal land resources.

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Table 1. Lands managed by federal agencies, areas of individual ecosystems, and their changes as of 2050 from the baseline 2005 under IPCC SRES scenarios in the CONUS

Federal agency	IPCC scenario	Ecosystem and area, km^2									
		Croplands	Forests	Grasslands	Hay/pasture	Mech_ disturbed	Other	Shrublands	Wetlands	Total	%
BLM	Baseline (2005)	2,563	64,356	95,381	3,213	875	47,244	494,413	1,031	709,075	38.3
BOR		200	494	1,138	313	0	4,219	4,425	231	11,019	0.6
DOD		1,406	18,281	12,119	1,763	144	28,381	38,400	3,350	103,844	5.6
FS		7,213	557,150	95,900	11,375	7,956	23,075	127,700	18,750	849,119	45.8
FWS		2,681	4,744	5,694	1,350	63	9,356	18,125	12,781	54,794	3.0
NPS		244	32,550	8,738	431	38	17,094	44,975	6,944	111,013	6.0
Other		138	1,194	1,381	44	44	481	6,725	163	10,169	0.5
TVA		44	1,456	0	175	19	1,594	0	81	3,369	0.2
Sum		14,488	680,225	220,350	18,663	9,138	131,444	734,763	43,331	1,852,400	100
% of the total		0.8	36.7	11.9	1.0	0.5	7.1	39.7	2.3	100	
2050, km^2	Average*	19,429	668,721	216,729	23,798	15,467	135,013	729,863	43,381	1,852,400	
†Change %		34.1	−1.7	−1.6	27.5	69.3	2.7	−0.7	0.1	0	
2050, km^2	A1B	22,856	662,350	213,981	28,694	18,913	136,338	726,194	43,075	1,852,400	
†Change %		57.8	−2.6	−2.9	53.8	107.0	3.7	−1.2	−0.6	0	
2050, km^2	A2	20,144	664,325	217,231	24,875	16,856	135,700	730,106	43,163	1,852,400	
†Change %		39.0	−2.3	−1.4	33.3	84.5	3.2	−0.6	−0.4	0	
2050, km^2	B1	15,288	679,488	218,975	17,825	10,631	133,000	733,288	43,906	1,852,400	
†Change %		5.5	−0.1	−0.6	−4.5	16.3	1.2	−0.2	1.3	0	

BLM, Bureau of Land Management; BOR, Bureau of Reclamation, Department of Interior; DOD, Department of Defense; FS, Forest Service; FWS, Fish and Wildlife Service; NPS, National Park Service; TVA, Tennessee Valley Authority.

*The average of the results from all A1B, A2, and B1 scenarios.

†Change percentage by 2050 from the baseline 2005 land area of the same ecosystem.

grasslands, and shrublands. Taking the land area in 2005 as the footprint, as of 2050, the area of croplands would increase by 34% and the forests under mechanical disturbances may increase by 70% due to economic and demographic impacts embedded in the scenarios A1B and A2 (Table S1). Meanwhile, the area of forests, grasslands, and shrublands would decrease by 1.7%, 1.6%, and 0.7%, respectively. The greatest increase in croplands, hay/pasture, and mechanically disturbed forests would occur with A1B (then A2) at a cost of forests and grasslands. These changes would mainly take place in the lands owned by Bureau of Land Management (BLM) and USDA Forest Service (FS).

Baseline Ecosystem C Stock and Density. The baseline C stocks (averaged from 2001 to 2005) for each ecosystem are presented in Table 2. The total ecosystem C storage in all federal lands was 11,613 Tg C (1 Tg = 10^{12} g) in the end of 2005, contributed primarily by forests (~75%), shrublands (12%), and wetlands (9%). In association with federal agencies, more than 72% of the total ecosystem C was stored in the lands owned by FS, 15% by BLM, and <1% by Bureau of Reclamation (BOR), Tennessee Valley Authority (TVA), and "Other" classes.

In fact, the difference in land area for either ecosystem or federal agency (Table 1) makes it difficult to determine the real capacity of storing C or sequestrating atmospheric C by each individual ecosystem. Therefore, we weighted the C density for each ecosystem by area (Table 2). On average, the baseline ecosystem C density for all federal lands was about 63 Mg C·ha^{-1} but varied substantially from one ecosystem to another within an agency. For example, wetlands have the highest C density at 151 Mg C·ha^{-1}, followed by forests at 128 Mg C·ha^{-1}, and 19 Mg C·ha^{-1} for shrublands. The total ecosystem C stock magnitude depends on both the land area and C density of each individual ecosystem.

Because of both a large total land area and a high C density, federal forests made a dominant contribution to the total ecosystem C stock in all federal lands. The forests managed by FS in the Pacific Coast and Rocky Mountain regions stored about 8,278 Tg C in 2005 (7), which was equivalent to 180 Mg C·ha^{-1}. Our average estimate either for all federal forests (128 Mg C·ha^{-1} in Table 2) or for the FS-owned forests (131 Mg C·ha^{-1}) is smaller than the estimate (145 Mg C·ha^{-1}) for all forests in the western United States (8) because the latter included nonfederal forests in the West.

Projected Ecosystem C Dynamics in the Future. The projected ecosystem C stocks as of 2050 for three IPCC SRES scenarios are presented in Table 2. The total C stock in 2050 would be 13,865 Tg C (average across the three scenarios), representing a total gain of 2,252 Tg (19.4%) compared with that in 2005. The primary contribution comes from forests. Of the total C stock increase (2,252 Tg C) from 2006 to 2050, 76.3% would come from forests, almost 10% from wetlands, another 10% from grasslands, and only 1.6% from agricultural lands. Shrublands may become a small C source by losing 53 Tg C (about 4% reduction in C stock) that offsets the total C gain by 2.4%. The maximum change (increase) in C stock from the baseline could happen to the mechanically disturbed forests (177% under A1B, 145% under A2, and 50% under B1), followed by croplands and hay/pasture.

The total C stocks would also vary with IPCC SRES scenarios because of variations in socioeconomic and climate assumptions (Table S1). For example, compared with the scenario B1 (focused on environmental protection), the scenarios A1B and A2 (both focused on economy and population growth) would lead to a reduction in the ecosystem C stock by 251 and 206 Tg C, respectively. These ecosystem C losses could be dominantly attributed to the increase in forest cutting and conversions of forests, grasslands, and shrublands to agriculture and urban land uses.

Changes in Ecosystem C Density from the Baseline. The projected net changes in ecosystem C density (in megagrams of carbon per hectare) as of 2050 are presented in Table 2. Generally, the average C density was projected to increase to 75 Mg C·ha^{-1} by 2050 from 63 Mg C·ha^{-1} in 2005, implying an increase of 12.2

Table 2. Baseline and projected ecosystem carbon stock, and density, and annual sequestration rate as of 2050 for each ecosystem of federal lands across CONUS

Carbon measurement	Unit	SRES scenario	Cropland	Forest	Grassland	Hay/pasture	Mech_ disturbed	Other	Shrubland	Wetland	Sum/mean	SD
Carbon stock*	10^{12} g C	Baseline	53	8,728	604	55	68	60	1,389	656	11,613	
	% of total		0.5	75.2	5.2	0.5	0.6	0.5	12.0	5.6	100	
Carbon density	Mg C·ha^{-1}		36.6	128.3	27.4	29.6	74.2	4.6	18.9	151.3	62.7	
	SD		10.1	19.5	4.6	9.3	24.6	2.9	5.0	51.6	27.0	
Carbon stock†	10^{12} g C	A1B	105	10,300	805	108	188	64	1,320	876	13,766	
		A2	93	10,363	817	94	166	65	1,339	874	13,811	
		B1	69	10,674	828	62	102	58	1,348	877	14,017	
		Average	89	10,446	817	88	152	62	1,336	876	13,865	134
NECB‡	10^{12} g C	Average	36	1,718	213	33	84	2	−53	220	2252	
Carbon density	Mg C·ha^{-1}	Average	45.9	156.2	37.7	36.9	98.2	4.6	18.3	201.9	74.8	75.1
		Change§	9.3	27.9	10.3	7.3	24.0	0.0	−0.6	50.6	12.2	17.3
		SD	3.7	17.9	1.7	2.7	13.6	0.2	0.7	19.6	7.5	
Carbon sequestration rate¶	kg C·ha^{-1}·y^{-1}	A1B	212	604	227	177	556	2	−16	1,159	258	393
		A2	214	615	227	179	541	4	−13	1,138	264	386
		B1	192	639	231	117	484	−6	−11	1,074	288	373
		Mean	207	620	228	163	534	0	−13	1,124	270	383
		SD	82	398	37	61	303	5	17	436	168	

*Ecosystem carbon stock, including aboveground and belowground biomass and soil organic carbon in the top 20-cm depth of soil from the average of three carbon simulation models.
†Ecosystem carbon stock, including aboveground and belowground biomass and soil organic carbon in top 20-cm depth of soil, averaged from three carbon simulation models with three GCM climate data and three SRES scenarios A1B, A2, and B1.
‡Net ecosystem carbon budget (NECB) between 2006 and 2050, or NECB = C $Stock_{2050}$ − C $Stock_{2005}$.
§Change in megagrams of carbon per hectare as of 2050 from the baseline 2005 for the same ecosystem of all federal lands.
¶Annual carbon sequestration rate averaged of the period from 2006 through 2050.

(±17.3) Mg C·ha^{-1}, but would vary substantially with individual ecosystems, ranging from a small source of 0.6 Mg C·ha^{-1} in shrublands to a big sink of 50.6 Mg C·ha^{-1} in wetlands over the 45-y period. The net change magnitude would also depend on IPCC SRES scenarios: smaller under B1 than under either A1B or A2.

Ecosystem C Sequestration Potential in the Future. As presented in Table 2, the average annual ecosystem C sequestration rate from 2006 to 2050 would be 270 kg C·ha^{-1}·y^{-1} for all federal lands but would vary substantially with individual federal agencies (±168 kg C·ha^{-1}·y^{-1}) and ecosystems (±383 kg C·ha^{-1}·y^{-1}). Among individual ecosystems, the net C flux would vary from a C source at a rate of 13 kg C·ha^{-1}·y^{-1} in shrublands to the greatest C sink at a rate of 1,124 kg C·ha^{-1}·y^{-1} in wetlands. Forests would have the second highest C sequestration rate of 620 kg C·ha^{-1}·y^{-1}. Finally, either C sinks or sources and their magnitudes as of 2050 at the ecosystem scale would vary with IPCC SRES scenarios, being the highest under scenario B1, because B1 aims to integrate conservational practices into land use and management that would help sequester more atmospheric C into biomass and soils compared with either A1B or A2. Their spatial distributions are illustrated in Fig. 1.

Discussion

Ownership-Related Changes in Federal Lands. The total area of federal lands and the land area owned by each federal agency have changed over time and would continue changing in the future. For example, from 1990 to 2010, the total area of federal lands had declined by almost 1% (more than 18 million acres) (9), even though the federal agencies had acquired many new parcels of land at the same time. However, no changes in the total area of federal lands were assumed to occur between 2006 and 2050 in this study due to the difficulty in projection.

Issues on the Presence of "Croplands" and Its Future Areal Change. The presence of "croplands" in federal lands could be attributed to the following:

i) The 1902 Reclamation Act intended to protect watersheds on federal lands and reclaim arid western lands through large-scale irrigation and flood control projects. The lands with soil and water supply conditions suitable for crop or pasture production were leased to farmers for agricultural use (1).
ii) The lands originally in agricultural use but sparsely distributed were required to combine with adjacent large federal land areas for specific integrated purposes, such as national or state park or conservation programs. These agricultural lands could be kept and leased to farmers for continuing agricultural use.
iii) Interpretation of remotely sensed images could misclassify other lands as agricultural lands, especially for the 1992 National Land Cover Dataset, which came with about 30% uncertainty (10); this category is a combination of cropped lands and hay/pasture in which hay, pasture, or both might be dominant in the broad category.

Because of the presence of croplands in the baseline, the future LULC projections could carry over and enlarge the interpretation error of agricultural land. That may be why a big areal change (increase) was projected for the agricultural land category from 2006 to 2050 despite its minor proportion in all federal lands.

Major Differences from Nonfederal Lands.
Areal proportions of individual ecosystems. If defining the lands that exclude federal lands as nonfederal lands, the areal proportion of each ecosystem in the total land area is quite different between federal lands and nonfederal lands (Table 3). Of all federal lands, grasslands and shrublands together account for 51.6%, followed by forests (37.2%), with agricultural lands composing merely 1.8%. Of all nonfederal lands, agricultural lands, grassland/

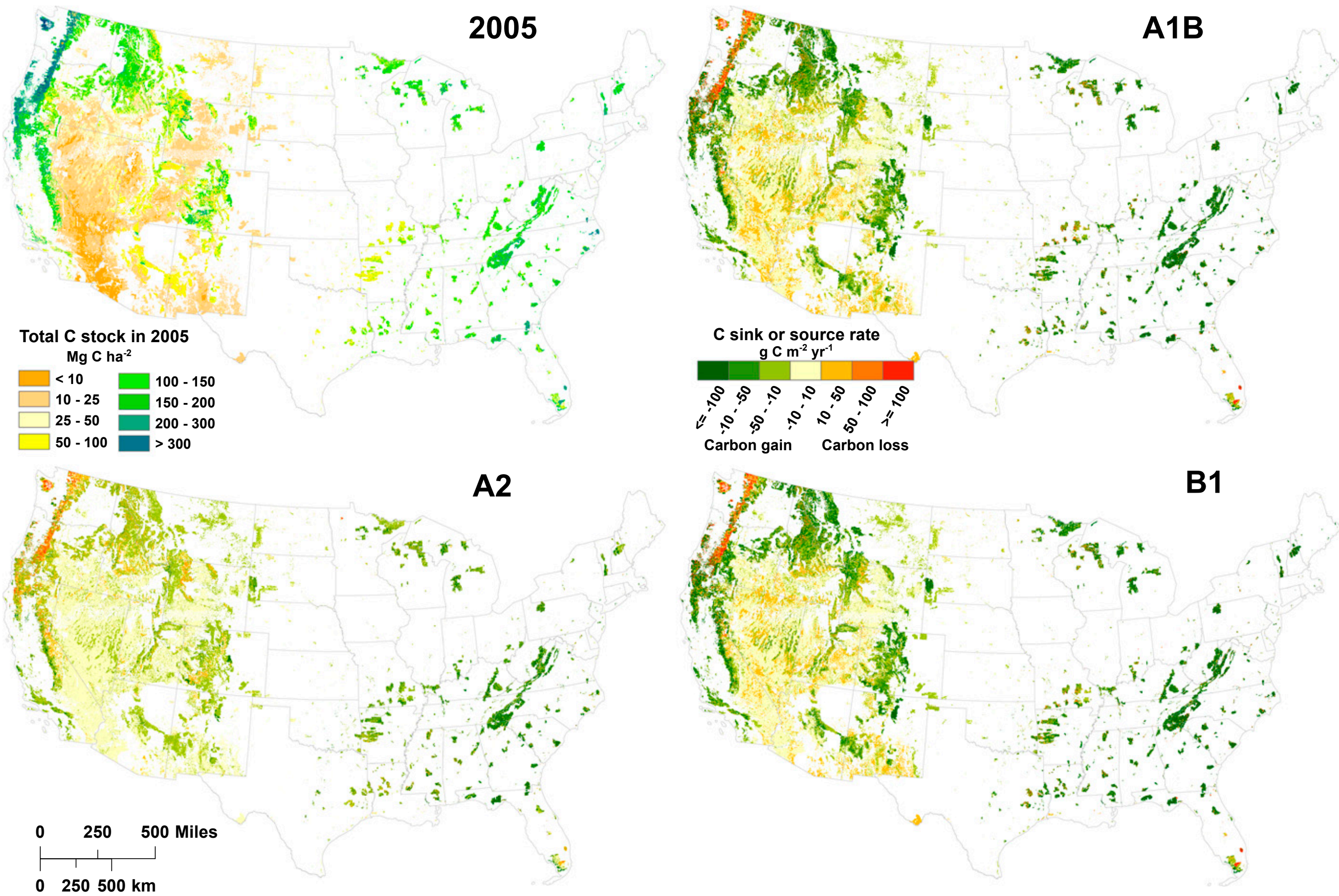

Fig. 1. Spatial distribution of the baseline ecosystem carbon stock (in vegetation and the top 20-cm depth of soil, averaged from three GCMs and three models) in federal lands across the CONUS and its changes from 2006 to 2050 under three scenarios, A1B, A2, and B1.

shrublands, and forests are dominant, accounting for 33.2%, 28.2%, and 27.1%, respectively.

Baseline and projected ecosystem C stocks and their changes. In terms of changes in ecosystem C stock from 2006 to 2050 in Table 3, for federal lands, 80.0% would come from forests and only 3.1% from agricultural lands; for nonfederal lands, their contribution would be 58% and 19%, respectively. The average C density is much higher in nonfederal lands than in federal lands and shows a big increase from 75 kg C·ha^{-1} in 2005 to 87 kg C·ha^{-1} in 2050. Accordingly, nonfederal lands demonstrate a much higher annual net ecosystem C flux than do federal lands at the CONUS and individual ecosystem scales. Thus, the contribution of federal lands to the national ecosystem C budget could decrease from 23.3% in 2005 to 20.8% in 2050.

The higher annual C sequestration rate in nonfederal forests than in federal forests may be attributed to more younger trees in nonfederal forests (11) because more logging occurs in nonfederal forests and younger trees grow faster and accumulate more biomass per unit area than older trees do (12). According to Conner and Thompson (13), forests have a much higher net annual growing-stock growth rate in north, south, and Pacific coast regions than in Rocky Mountain regions where almost all forests are managed by federal agencies and showed a decline in net growth since the beginning of the 1990s.

Implications. Federal lands in the CONUS consist dominantly of forests, grasslands, and shrublands that are managed primarily by DOI agencies and the FS. Besides unfavorable biophysical conditions and a lower degree of human disturbances on these lands, a federal agency's land use policies and management practices could continue to be a strong force driving ecosystem C dynamics in the future. According to "a strategy for improving the mitigation policies and practices of the Department of Interior" (5), each federal agency can make the agency missions-oriented land use plans and decide management practices of its lands to enhance C sequestration (sinks) as opposed to nonfederal lands. The information presented herein about the spatially explicit baseline ecosystem C stock and C sequestration potential over time can be used as a fundamental reference for instituting federal agencies' policies and practices to mitigate GHG emissions from a specific ecosystem and sustain federal land resources.

Because of limited relevant data available for federal lands, there is a lack of deep exploration on both natural and anthropogenic ecosystem processes in this paper. Therefore, this study suggests that future research on federal lands' C dynamics and resilience may include the following: (*i*) effects of major land management activities, especially forest thinning and rangeland grazing, on ecosystem C and GHG fluxes; (*ii*) feasible measures that are needed to prevent shrublands from being C sources; (*iii*) more field observations for evaluating differences between federal and nonfederal lands; and (*iv*) the role of agency missions-oriented management practices in ecosystem C dynamics because of the differences in policy, primary goal, and management practices.

Materials and Methods

Federal Lands in the CONUS. The total area of the CONUS federal lands is about 1.852 million km^2 and managed by different federal agencies such as BLM, BOR, Department of Defense (DOD), USDA FS, Fish and Wildlife Service (FWS), National Park Service (NPS), and TVA. Of all federal lands, 45.8% is

Table 3. **Characteristic comparisons between federal lands and nonfederal lands**

Land use/land cover							
Time	Unit	Agriculture*	Forests	Grassland/shrubland	Other	Wetlands	Total/mean
Federal lands							
2005	Land area, km^2	33,150	689,363	955,113	131,444	43,331	1,852,400
2050		43,227	684,188	946,592	135,013	43,381	1,852,400
2005	Areal % of the total	1.8	37.2	51.6	7.1	2.3	100
2005	Ecosystem C stock, Tg	108	8,796	1,993	60	656	11,613
2050		177	10,598	2,153	62	876	13,865
Change from 2005	Tg	69	1,802	160	2	220	2,252
Contribution to change, %		3.1	80.0	7.1	0.1	9.8	100
2005	C density, Mg C·ha^{-1}	33	128	21	5	151	63
2050		40	129	30	11	138	64
Sequestration rate	kg C·ha^{-1}·y^{-1}	185	607	42	0	1,124	270
Nonfederal lands†							
2005	Land area, km^2	1,999,561	1,634,439	1,701,953	424,468	268,265	6,028,685
2050		2,207,092	1,527,454	1,477,775	551,224	266,183	6,028,700
2005	Areal % of the total	33.2	27.1	28.2	7.0	4.4	100
2005	Ecosystem C stock, Tg	7,956	21,013	5,144	483	3,714	38,310
2050		10,669	29,354	6,374	753	5,473	52,622
Change from 2005	Tg	2,713	8,341	1,229	270	1,759	14,313
Contribution to change, %		19.0	58.3	8.6	1.9	12.3	100
2005	C density, Mg C·ha^{-1}	41	155	23	5	202	75
2050		48	192	43	14	206	87
Sequestration rate	kg C·ha^{-1}·y^{-1}	190	1,414	287	51	1,493	528

*Includes both croplands and pasture/hay classes.
†Synthesized from Zhu and Reed (18, 19).

managed by FS, 38.3% by BLM, 6.0% by NPS, and 5.6% by DOD (Table 1). The major LULC types (or ecosystems) include shrublands, forests, grasslands, and wetlands, accounting for 39.7%, 36.7%, and 11.9%, respectively. Agriculture is relatively rare on federal lands, consisting of about 1% hay/pasture and 0.8% croplands. The spatial distribution of individual ecosystems is illustrated in Fig. 2.

Methodology Framework. We used the methodology developed for national biological C sequestration potential assessment (14) that was mandated by the Energy Independence and Security Act of 2007 (15). In general, the methodology framework for this study was based on a multimodel system platform to (*i*) synthesize existing data to form input datasets such as remote sensing imagery, soil inventories, historical climate records, and measurement observation datasets; (*ii*) link LULC, land management, and climate data with statistical and process-based models to quantify spatially and temporally explicit baseline ecosystem C stocks (average from 2001 to 2005); and (*iii*) use contemporary LULC data derived from downscaled IPCC SRES scenarios A1B, A2, and B1 (Table S1) to estimate future annual C change rates (from 2006 to 2050) at an individual ecosystem scale. To illustrate uncertainties stemming from inherent biases of individual models, multiple models were automatically linked to run in an ensemble fashion on the General Ensemble Biogeochemical Modeling System (GEMS) (16) platform in which all models shared the same input data and generated results from each model independently for analyzing the range of uncertainties among three models.

Modeling Systems. Using multiple models could result in more useful information than any single model by clarifying uncertainties stemming from inherent biases of the individual models (e.g., refs. 17–19). Therefore, we used the well-established GEMS, which has encapsulated multiple site-scale biogeochemical models such as CENTURY (20), Erosion-Deposition C Model (EDCM) (21), and Land Greenhouse-Gas Accounting Tool (LGAT) (19). GEMS can drive these models simultaneously to perform ecosystem dynamics simulations over time and space and has been successfully used at diverse spatial scales (e.g., refs. 16, 18, and 19). It is a type of LULC change-oriented, regional biogeochemical simulation system with multiple encapsulated ecosystem models. As an interface and platform, GEMS framework assists users with getting standardized data into and out of the biogeochemical models that are staged on the GEMS platform. The details in model inputs can be seen from Tables S2 and S3.

The major biogeochemical processes of both EDCM and CENTURY models include net primary production (NPP), photosynthetic allocation, litter fall, mortality, decomposition of plant tissues, and soil organic carbon (SOC). There is no need to predetermine endpoints of maximum C-carrying capacity or predefine paths to describe how the endpoints are approached, because the dynamics of vegetative and SOC pools are controlled by the fluxes of inputs and outputs. The endpoints and paths are tightly coupled with and regulated by nitrogen and water cycles, land uses, management activities, etc. For model evaluation, we selected the most sensitive parameter (PRDX) to calibrate the plant production using observed grain yield for croplands (e.g., corn and soybean) and the moderate-resolution imaging spectroradiometer (MODIS) NPP for noncroplands (e.g., forest and grasslands) (22). The models have been well calibrated and validated at regional and national scales (18, 19, 22).

LULC Projections. LULCs and their changes are one of critical forces driving ecosystem C dynamics. Forecasting Scenarios of Land Use (FORE-SCE) model

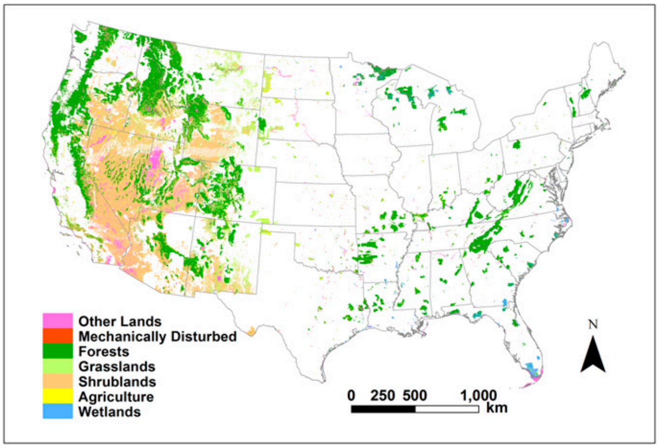

Fig. 2. Federal lands across the CONUS and distribution of major LULC types (or ecosystems).

(23, 24) was used to produce spatially explicit LULC maps consistent with the IPCC SRES scenarios. Downscaled SRES scenarios (*SI Appendix*, section 2.1) were used as a "prescription" for future proportions of LULC change. LULC maps at 250-m resolution were produced for each year of the baseline period from 1992 through 2005 and for three SRES scenarios of future LULC change from 2006 through 2050. Meanwhile, three downscaled (to the continental United States and Canada) global climate models (GCMs) (MIROC 3.2-medres, CSIRO Mk3.5, and CCCma CGCM3.1) for climate projections associated with each IPCC SRES scenario (25, 26) were processed as model inputs.

Ensemble Modeling. Multiple model simulations were run on the GEMS platform continuously for 1992 through 2050. EDCM and CENTURY were run at monthly time steps with a sampling intensity of 1% (or 1 pixel for each 10 pixels in the *x* direction and 10 pixels in the *y* direction) as suggested by our preliminary study to speed model simulations and reduce computation load. LGAT was run at annual time steps on a per-pixel basis because of the much shorter time for each run compared with the other two models.

Three LULC scenarios developed from IPCC SERS A1B, A2, and B1, along with three climate change projections of GCMs were incorporated into GEMS simulations of ecosystem C dynamics and run for the same land base from 1992 through 2050, using 1992 through 2000 as the model spin-up, 2001 through 2005 as the baseline period, and 2006 through 2050 as the future projection period.

A total of 21 model runs were performed based on the combinations of models, LULC scenarios, and GCM projections (not 27 model runs because the LGAT was designed for three LULC scenarios only).

The model output variables were defined by Zhu (14), and the major outputs for this study include NPP, grain production, and annual C pools in vegetation and soils for each ecosystem.

More details about input data, ensemble modeling, defining the baseline ecosystem C stock and future C sequestration rates, and processing model outputs are presented in *SI Appendix*.

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Supporting Information

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SI Appendix

1. Baseline Land Use and Land Cover Between 1992 and 2005. The baseline period was defined from 1992 to 2005 for this study to examine changes in recent land use and land cover (LULC) (or ecosystem) and calibrate both the LULC and biogeochemical modeling frameworks before projecting future LULC. The year 1992 was chosen as the starting year because this is when the earliest consistent, nationwide, high–spatial-resolution LULC data were available. A modified version of the 1992 National Land Cover Dataset (NLCD) was used to serve as the initial LULC data. This dataset also has the advantage of having been extensively assessed for accuracy (10). The year 2005 was chosen as the endpoint for the baseline period so as to fully use the consistent, spatially explicit, nationwide LULC data.

FORE-SCE model (23, 24) was used to generate the LULC baseline because of its ability to precisely match prescribed proportions of LULC changes and thus replicate the historical amounts of LULC changes. The model runs were rejected if FORE-SCE could not accurately replicate the prescribed quantities of LULC changes for any reason. The modeling results of the LULC baseline from 1992 through 2005 would be evaluated independently at an ecoregion scale using a visual assessment of the spatial LULC distribution based on historical and current patterns of changes, LULC patch size characteristics, spatial arrangement and context, and dispersion patterns. An unacceptable distribution of LULC changes resulted in a reparameterization of FORE-SCE model, and a subsequent new model run was initiated and repeated until model performance was deemed acceptable.

2. LULC Trends Following IPCC SRES Scenarios from 2006 to 2050.

2.1. IPCC SRES scenario downscaling. To use the IPCC SRES (6) while maintaining consistency with the original dataset and local data at a regional scale, an accounting model was developed to refine the national-scale integrated assessment model (IAM) projections from a global IAM and to downscale to hierarchically nested ecoregions. These downscaled ecoregions were then converted to form annual LULC maps until 2050 using a spatially explicit LULC change model (26). The downscaled IPCC SRES scenarios for the conterminous United States (CONUS) are presented in Table S1.

Technically, the national-scale LULC projections were generated with the Integrated Model to Assess the Global Environment (IMAGE) (27), land use histories, and expert knowledge. The IMAGE was used to simulate future environmental changes tied with scenarios A1B, A2, and B1 for the CONUS that was treated as a single region (Table S1). Initial quantities of projected LULC changes were formulated in a scenario named "demand" with an accounting model for downscaling land use scenarios (26).

The historical land use data came primarily from USGS Land Cover Trends Project, which provided ecoregion-based estimates on the rate, extent, and type of LULC changes for multiple dates between 1973 and 2000 (28 and 29). These data were incorporated into the construction and downscaling of IPCC SRES scenarios in two ways: (*i*) expanding projections of the net changes in development, mining, and LULC classes of agricultural lands into gross conversions between all primary LULC classes at the national scale; and (*ii*) downscaling proportionally these LULC conversions to CONUS ecoregions using the method of Sleeter et al. (26). Similarly, three climate change projections from the general circulation models (GCMs) were also downscaled to a national and regional scale for the CONUS (26) and used in the study.

2.2. LULC trends from 2006 to 2050. The FORE-SCE model was used to produce spatially explicit LULC maps consistent with the downscaled IPCC SRES scenarios. Downscaled scenarios described above were used as a "prescription" for the proportions of LULC changes. Probability-of-occurrence surfaces were used to guide the placement of future changes at a regional scale, with spatial characteristics of land change patches parameterized using historical land cover data from the USGS Land Cover Trends Project (28). The FORE-SCE model also produced annual maps of forest stand age, initialized through interpolating USDA Forest Service Forest Inventory and Analysis (FIA) data, and updated in each annual model run as a forest pixel was harvested, or when there was afforestation or forest regrowth. The FORE-SCE model produced annual, spatially explicit maps of LULC and stand age from 2006 to 2050 for each SRES scenario, with 17 unique LULC classes at a 250-m resolution.

It is impossible to validate the projected LULC changes because of no references available for a future time frame. However, the proportions of the projected LULC changes associated with SRES scenarios were used to bound overall uncertainties regarding future LULC proportions. In other words, the differences in projected LULC proportions between scenarios were examined using a quantitative disagreement measurement. The spatial modeling component of the FORE-SCE model introduced the allocation disagreement between scenarios in which the spatial pattern at a pixel level may differ between two scenarios even if the prescribed scenario LULC proportions were similar. Applications of quantitative and allocation disagreement measurements to each pair of the three scenarios allowed for a determination of whether the per-pixel differences between scenarios maps were because of the scenario LULC prescriptions themselves or were a result of the spatial modeling and the placement of LULC changes (24).

3. Baseline Ecosystem C Stock and Net Ecosystem C Budget as of 2050. As described above, the methodology framework is both spatially and temporally explicit. The spatial foundation of the assessment is the LULC modeling component, in which LULC types were mapped seamlessly, and all pixels were partitioned into LULC and LULC-change classes. Biogeochemical models (see below) were used to estimate the baseline and future terrestrial ecosystem C stocks, whereas the GCMs were incorporated into the assessment to analyze the effects of the downscaled SRES scenarios A1B, A2, and B1 as defined in Table S1. Both current and future changes in C stock were estimated to establish a baseline and provide a range of potential C sequestration capacities, respectively. The baseline ecosystem C stock for this assessment was defined as the average C stock for the period from 2001 to 2005. The year 2001 was chosen as the starting year when the earliest consistent, nationwide, and high–spatial-resolution LULC data were available. The baseline period of 1992–2001 was set for retrieving the trend of LULC to facilitate model spin-up.

4. Modeling Systems. According to the methodology for national biological C sequestration potential assessment project (14), which was mandated by the Energy Independence and Security Act of 2007 (15), the CENTURY (20), Erosion-Deposition C Model (EDCM) (21), and Land Greenhouse-Gas Accounting Tool (LGAT) (19) were used to run in an ensemble fashion on the General Ensemble Biogeochemical Modeling System platform (GEMS) (16) by sharing the same input data, because these models have already been linked with GEMS previously and were used consistently for national biological C sequestration potential assessment (14, 18, 19).

4.1. Model run setup.

Model initialization. Soil properties derived from the SSURGO database were used as initial values for biogeochemical simulations.

Major soil properties include soil thickness, SOC content, texture (fractions of sand, silt, and clay), bulk density, and drainage. The total SOC pool was partitioned into active (5%), slow (45%), and passive (55%) classes for CENTURY and EDCM initialization (21). Forest biomass C pools (aboveground and belowground live biomass or dead biomass consisting of forest litter and dead, woody debris) from Forest Service FIA were initialized using the initial forest age map, forest type (evergreen, broadleaf, and mixed), and the relation between forest age and C stock (including the effects of demographics and age-related growth). Moreover, the effects of CO_2 fertilization and N deposition were also included in modeling to count forest biomass. For consistency and avoiding potential errors, the initialization of the SOC and biomass was done using LGAT, and the outputs from LGAT for 1992 (the first year of the model simulations) were then read directly by CENTURY and EDCM as initial conditions.

Model calibration and validation. Model calibration and validation were only performed for CENTURY and EDCM, because all coefficients of LGAT could be derived directly from field measurements. The observed data for calibration (from 2001 through 2005) included 250-m-resolution moderate-resolution imaging spectroradiometer (MODIS) net primary productivity (NPP) data for forests and grasslands (30). County grain yield statistics by crop types from USDA National Agricultural Statistics Service (NASS) were used to parameterize crop yield because the MODIS NPP was found to have inconsistent performance for calibrating crop production. An automated calibration was implemented with Shuffled Complex Evolution (SCE-UA) method (31) and R-Language Flexible Modeling Environment (R-FME) software package. The potential maximum production parameter (PRDX) was adjusted with the USDA county statistics of grain yield and the county MODIS NPP of forest biomass from 2001 through 2005.

Observation data for model validation include USDA forest biomass values (32), aboveground biomass from Woods Hole Research Center National Biomass and C Dataset for the Year 2000 (33), the MODIS-derived NPP (30), and the USDA NASS grain yield for 2006, 2008, and 2010. Maps, binned scatterplots, and correlation plots were generated for different ecosystems to compare the simulated results of biogeochemical models with observations. Simple linear-regressions, R^2, and root-mean-square errors between the observed and modeled data were computed to evaluate the performance of the models. Some of the results of the validation can be obtained from Zhu and Reed (18).

4.2. Input data. Besides IPCC SERS-associated variables for the downscaled LULC projections, other major inputs for model simulations are listed in Tables S2 and S3. In terms of the data coverage, all of the input data layers from various sources were first converted to standard resolutions and projections in a standard format (NetCDF) for the CONUS, and their time-series data covered a 59-y time frame from 1992 to 2050 (34) except for the grain yields, which are not available for the projection period. The clear-cutting information was used to define "mechanically disturbed forests" in this study.

4.3. Ensemble modeling. Multiple GEMS simulations were run continuously for 1992 through 2050 with the following setup.

i) Three models were run on the GEMS platform. CENTURY and EDCM were run at monthly time steps with a sampling intensity of 1% (or 1 pixel for each 10 pixels in the *x* direction and 10 pixels in the *y* direction). The validity of the sampling rate was confirmed by comparing the results with those produced with per-pixel simulations. The LGAT was run at annual time steps on a per-pixel basis because the time for each run was much shorter than the other two process-based models.

ii) Three LULC scenarios were developed and projected in line with the downscaled IPCC SRES scenarios A1B, A2, and B1, respectively.

iii) Three GCM (MIROC 3.2-medres, CSIRO Mk3.5, and CCCma CGCM3.1) climate change projections (25) associated with each LULC scenario were processed. Each of the GCMs corresponded to one of the IPCC SRES scenarios.

iv) The model simulations were run for the same land base from 1992 through 2050 with the period from 1992 to 2000 as the model spin-up, then 2001 through 2005 as the baseline period, and 2006 through 2050 as the projection period. Major land disturbances and their characteristics used in model simulations are presented in Table S3.

Both CENTURY and EDCM were designed to generate results for each combination of three GCM projections and three IPCC SRES scenarios ($3 \times 3 = 9$ runs), and LGAT was designed to simulate effects of three IPCC SRES scenarios only, for a total of 21 runs. Because there were no alternative scenarios for climate and LULC data during the historical period, only three unique model simulations with no variation in LULC and climate were run for the period from 1992 through 2005.

5. Modeling Outputs and Their Analyses. The major model output variables include NPP, grain production, and dynamics of C pools of vegetation and soils for individual terrestrial ecosystems. Details in input data sources and output variables can be referred to Zhu (14) and Schmidt et al. (34).

The total ecosystem C stock refers to the C storage at the end of the specified year, including aboveground and belowground biomass and SOC pool in the top 20-cm depth of soil. The amounts of C removed from ecosystems by timber and grain harvest were tracked in GEMS, but the fate of the offsite C in timber and grain products was not tracked. Therefore, the offsite contribution of harvests was not included in this assessment. Fire emissions were tracked by GEMS according to the extent and severity data layers. When a land was converted from type A to type B, the emissions of C were added to cover type B, consistent to IPCC good practice guidance (35). The following variables were calculated, when appropriate, based on the model output variables mentioned above: (*i*) The annual C stock change in a given year (or the net C flux) was calculated as the stock difference between the year (t) and the previous year ($t - 1$) as $C_t - C_{t-1}$. (*ii*) The average annual net ecosystem C balance (NECB) during the projection period was calculated as the difference in the total ecosystem C stock between 2050 and 2005 divided by the duration (45 y) as follows: $NECB = (C_{2050} - C_{2005})/45$, where C_{2005} and C_{2050} represent the C stock at the end of 2050 and the end of 2005, respectively.

According to these calculations, a positive sign indicates C sequestration in terrestrial ecosystems (or C sinks) and a negative sign means C losses from terrestrial ecosystems (or C sources).

ACKNOWLEDGMENTS. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Table S1. Major forces driving LULC change in association with IPCC SRES scenarios and population growth

Driving force	IPCC SRES scenarios (6) for United States until 2050		
	A1B	A2	B1
Population growth (global and United States) (27)	Medium. Globally, 8.7 billion by 2050, then declining; in the United States, 385 million by 2050	High. Globally, 15.1 billion by 2100; in the United States, 417 million by 2050	Medium. Globally, 8.7 billion by 2050, then declining; in the United States, 385 million by 2050
Economic growth	Very high. US per-capita income $72,531 by 2050	Medium. US per-capita income $47,766 by 2050	High. US per-capita income $59,880 by 2050
Regional or global orientation	Global	Regional	Global
Technological innovation	Rapid	Slow	Rapid
Energy sector	Balanced use	Adaptation to local resources	Smooth transition to renewable
Environmental protection	Active management	Local and regional focus	Protection of biodiversity

Note: The IPCC SRES scenarios were used in this study because the new IPCC "Representative Concentration Pathways" (RCPs) were not available at that time when our study had been already conducted for more than 3 y.

Table S2. Input data used in models for the baseline and projected ecosystem C stock simulations

Data category	Data type	Data source/reference	Model		
			LGAT	EDCM	CENTURY
LULC	LULC classes	USGS NLCD 1992, 1997, 2001, 2006	x	x	
Climate	Monthly minimum and maximum temperature, monthly precipitation	PRISM Climate Group—baseline; CFS—projected (25)		x	x
CO_2 fertilization	CO_2 monthly concentration	IPCC (36)		x	x
Atmospheric N	Annual N deposition distribution	Dentener (37)		x	x
Soil	Total sand	SSURGO (USDA NRCS)		x	x
	Total clay			x	x
	Total silt			x	x
	Soil thickness			x	
	Soil organic carbon		x	x	x
	Available water capacity			x	
	DB 0.33 bar H_2O			x	
Forest	Biomass	USDA Forest Service	x		
	Stand age	USDA Forest Service; USGS Land Cover Trends Project	x	x	x
	FIA species growth curves, height, diameter, biomass measurements	USDA Forest Service	x		
	Timber product output	USDA RPA TPO	x		
Crops	Derived crop type	Schmidt et al. (34)	x	x	x
	USDA crop yield table	USDA NASS		x	x
	USDA fertilization table	USDA ERS		x	x
	USDA manure table	USDA ERS		x	x
	CTIC tillage table	CTIC; USDA ERS		x	x
Management	Derived manure	Schmidt et al. (34)	x	x	x
	Derived tillage	Schmidt et al. (34)	x	x	x
	Derived fertilizer	Schmidt et al. (34)	x	x	x
	Irrigation	USGS Irrigated Agr. Dataset	x	x	x
	Nitrogen deposition 1993 and 2050	Dentener (37)		x	x
Remote sensing	NPP	Zhao et al. (30)		x	x
Fire	Fire severity	Eidenshink et al. (38)		x	x
Reference	State and county FIPS	US Census Bureau	x	x	x
Initial condition	Forest litter biomass	Spreadsheet model		x	x
	Aboveground live biomass	Spreadsheet model		x	x
	Belowground live biomass	Spreadsheet model		x	x
	Deadwood biomass	Spreadsheet model		x	x
	Standing wood biomass	Spreadsheet model		x	x

Note: Most of the input data have a 250-m spatial resolution and variable temporal characteristics, even though most data cover the first decade of the 21st century. Db 0.33 bar H_2O, the oven-dry weight of the less than 2-mm soil material per unit volume of soil at a water tension of 1/3 bar (as used in the SSURGO database). CTIC, Conservation Technology Information Center; EDCM, Erosion-Deposition C Model; ERS, Economic Research Service; FIA, USDA Forest Service's Forest Inventory and Analysis; FIPS, Federal Information Processing Standard; LP DAAC, Land Processes Active Archive Center; LULC, land use and land cover; MODIS, moderate resolution imaging spectrometer on board NASA's Terra satellite; NASA, National Aeronautics and Space Administration; NASS, National Agricultural Statistics service; NPP, net primary productivity; NRCS, USDA's Natural Resources Conservation Service; NTSG, Numerical Terradynamic Simulation Group; PRISM, parameter-elevation regressions on independent slopes model; RPA, US Forest Service Forest and Rangeland Renewable Resources Planning Act of 1974; SSURGO, Soil Survey Geographic Database; TPO, timber product output; USDA, US Department of Agriculture.

Table S3. Major land management activities and natural disturbances used in model simulations

Type	Source/reference	Spatial resolution	Time period
Crop management			
Crop yield	USDA NASS crop yields	County	1992–2050
Fertilization	USDA ERS fertilization use	County	1992–2050
Manure	USDA ERS manure use	County	1992–2050
Tillage	Conservation Technology Information Center (CTIC)	County	1992–2050
Irrigation	USGS Irrigated Agr. Dataset	250 m	NA
Derived crop management			
Derived crop type, manure, tillage, and fertilizer	Derived grids for this study (34)	250 m	1992–2050
Fire			
Extent, severity, frequency	USGS Professional Report 1797 (18)	250 m	1992–2050
Forest clearcuts			
Forest-stand age	USGS Land Cover Trends Project	250 m	1992–2050
Timber product output	TPO form USDA FIA RPA	State	2009
Forest partial cutting			
Forest thinning ratio	USDA Forest Service FIA	FIA unit	NA
Forest disturbance			
Forest mortality ratio	USDA Forest Service FIA	FIA unit	NA
Drought			
Precipitation	PRISM Climate Group and CFS	250 m	1992–2050

Note: CFS, Canadian Forest Service; CTIC, Conservation Technology Information Center; NA, not applicable; NASS, National Agricultural Statistics service; PRISM, parameter-elevation regressions on independent slopes model; TPO, timber product output; USDA, US Department of Agriculture; USDA ERS, USDA Economic Research Service; USDA FIA RPA, USDA Forest Inventory Analysis Resource Planning Act; USGS, US Geological Survey.