

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 km²—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 = 10¹² 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 sequestering 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			Mech_							SD
		scenario	Cropland	Forest	Grassland	Hay/pasture	disturbed	Other	Shrubland	Wetland	Sum/mean	
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
		SD										
NECB [‡]	10 ¹² g C	Average	36	1,718	213	33	84	2	-53	220	2252	
		SD										
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	
		SD										
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 conservation 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:

- 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).
- 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.
- 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/

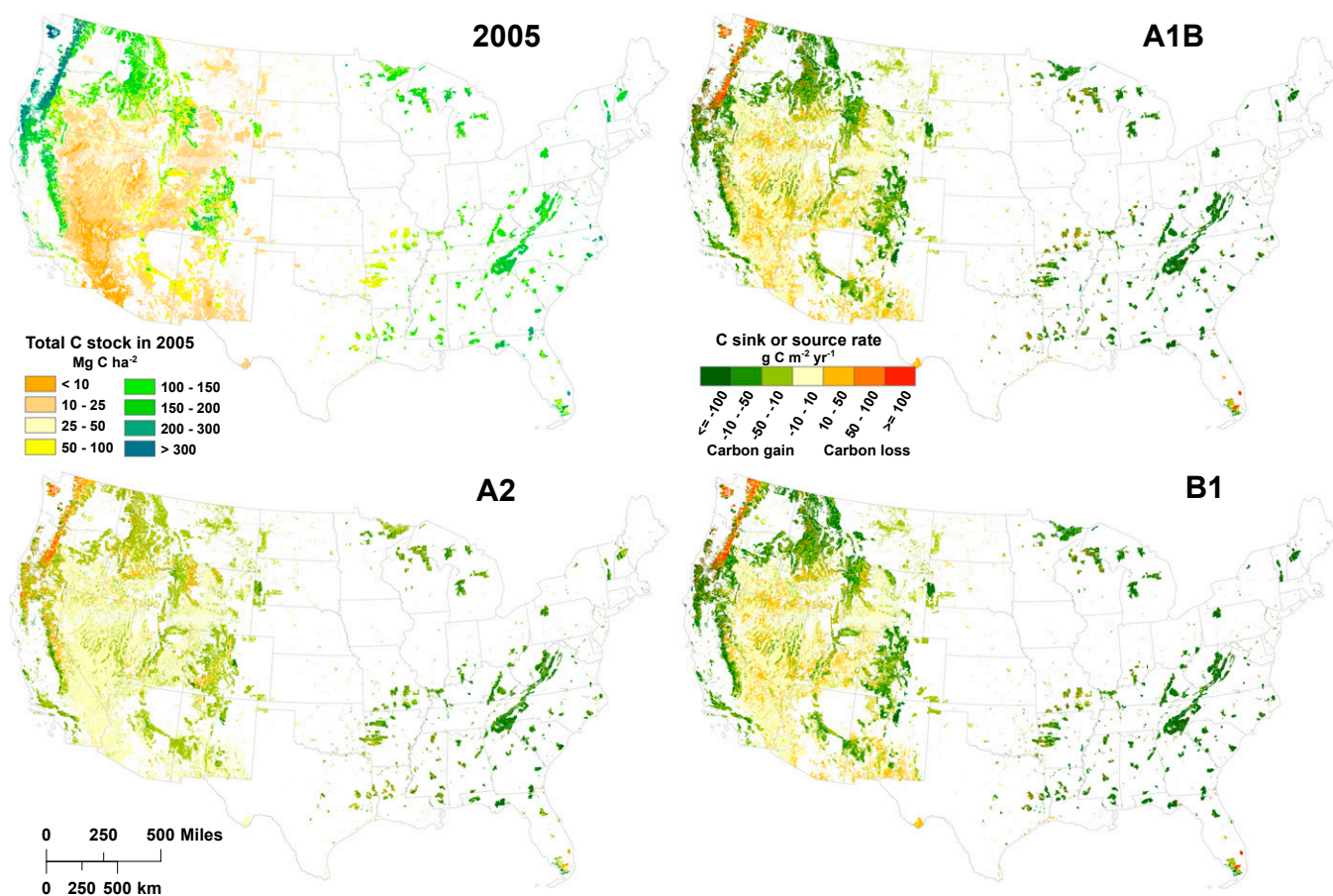


Fig. 1. Spatial distribution of the baseline ecosystem carbon stock (in vegetation and the top 20-cm depth of soil, averaged from three GCMs and three models) in federal lands across the CONUS and its changes from 2006 to 2050 under three scenarios, A1B, A2, and B1.

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 km² 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
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
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

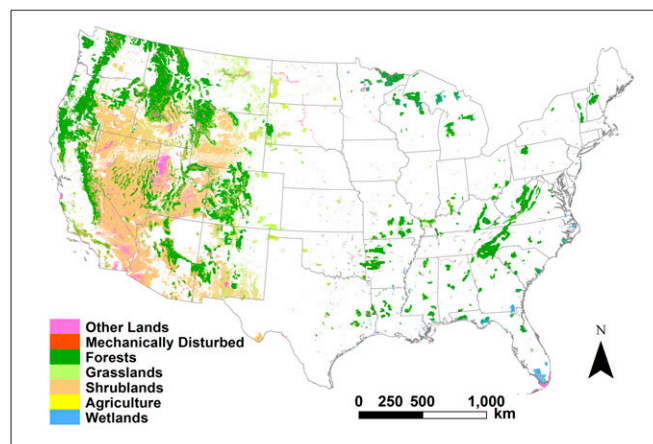


Fig. 2. Federal lands across the CONUS and distribution of major LULC types (or ecosystems).

(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 CCma 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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