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The Quantity and Controls on Soil Carbon in California and United States

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Summary

Soil organic carbon (SOC) and soil inorganic carbon (SIC) are huge carbon pools in the terrestrial ecosystems. Using the State Soil Geographic Database (STATSGO), we estimated that there are 316.03×10^8 to 1100.85×10^8 tons of SOC and 187.95×10^8 to 814.69×10^8 tons of SIC in the upper 2 m of the conterminous United States. Mollisols are the largest contributor to the national soil carbon stock, with $11{,}759 \times 10^6$ to $34{,}401 \times 10^6$ tons of SOC (accounting for about 31.3 to 37.3%) and $7{,}734 \times 10^6$ to $33{,}148 \times 10^6$ tons of SIC (about 40.7 to 41.2% of the national SIC total). For any of the three soil depths examined, forests contain the greatest national soil organic carbon (SOC) stock. However, the relative amount contained in the forests decreases as soil depth increases. Out of the total national SOC stocks at the three different soils depths, the forest ecosystems occupying 30.9% of the national land contain 30.4% (upper 0.2 m), 27.7% (upper 1 m), and 26.9% (upper 2 m) of the total stocks. Covering 18.0% of the national land, agricultural lands occupy 25.2% (upper 0.2 m), 25.7% (upper 1 m), and 25.3% (upper 2 m) of the corresponding total stocks, respectively. The ratios between SOC (or SIC) sequestrated in the surface layer (upper 0.2m) and that in the upper 2 m soil are lower in the managed ecosystems than those in the natural ecosystems, reflecting the fact that the managed ecosystems have generally experienced a loss of labile SOC and SIC in the surface layer as a result of cultivation. In the conterminous United States, SOC decreases as mean annual temperature (MAT) increases in the level landscape and lower elevation (< 600 m) of forest and grassland ecosystems. SOC decreases more rapidly as MAT increases in the surface layer than that in the subsurface layers, and in the regions with lower mean annual precipitation (MAP) than that in the regions with higher MAP, especially in grasslands. A GIS shell was developed to integrate CENTURY point soil carbon model with State Soil Geographic database (STATSGO) to simulate the response of soil carbon in terrestrial ecosystems to the climate or management change in California.

Keywords: *soil organic carbon; soil inorganic carbon; soil carbon variation, soil carbon controls*

Objectives

1. Determine the patterns (and total) of organic and inorganic C storage in the USA and California using a GIS framework and the STATSGO soil data base.

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2. Quantitatively examine, using a GIS framework, the relation of these patterns to climate, topography, geology, ecosystem type, and land use.
3. Calculate a simple, single C pool-based, soil C residence time for California and the USA using the approaches and data from objectives 1 and 2.
4. Incorporate multi-compartment soil C models (CENTURY) into a GIS-based framework to provide more realistic estimates of soil C turnover, and its response to environmental change, in California.

Approaches and Procedures

STATSGO (1997 version) was used to calculate soil organic carbon (SOC) and soil inorganic carbon (SIC) in California and the United States (SCS 1992). To calculate the quantity of SOC or SIC, STATSGO data was checked, and missing data (bulk density, organic matter, etc.) was estimated by the methods we proposed (based on soil types and locations to calculate local or global mean). The C data was then normalized for gravel content, since carbon data (SOC or SIC) in STATSGO was reported on a fraction < 2 mm in diameter; total SOC and SIC were calculated based on the low, high limits and midpoint approaches using Geographic Information System (GIS). To study the driving effects of "the state factors" on SOC and SIC, area extent of each ecosystem (agriculture, cultivated pasture, forest, grass, shrub, wetland) was extracted and aggregated from National Land Cover Data (NLCD) (Vogelmann et al. 1998). The ecosystems, topography (DEM) (Gesch and Larson 1996), climate (mean annual temperature MAT, and mean annual precipitation MAP) (Daly et al. 2001) were then overlaid, state by state, with the generated SOC and SIC maps to study their relationship with SOC or SIC. To estimate soil C residence times, the climate-driven estimates of soil respiration was calculated by $SR=(9.26 \times MAT)+(0.0127 \times MAT \times MAP) + 289$, where SR = soil respiration (g C m^{-2} yr^{-1}), MAT in ^{o}C, and MAP in mm (Raich and Schlesinger 1992; Raich and Potter 1995). The soil C patterns (g C m^{-2}) was then linked with soil respiration by the formula ($\tau = C/SR$) to derive single pool and first order decay model-based estimates of soil C residence times τ (years) (Jenkinson et al. 1991; Amundson 2001). A parameter attribute table (average monthly precipitation, average monthly minimum temperature, average monthly maximum temperature, soil properties) required by the CENTURY model was established for each map unit of STATSGO in California. A GIS interface was developed in Arcview with Avenue language to simulate soil carbon response to the climate or management change in California.

Results

Quantity of Soil Carbon in California and the Conterminous United States

1.1. Soil Carbon by State, Region, and the United States

SOC and SIC in the upper 2m of each state was presented in table 1. Texas has the largest SOC in the top 2 m soil with 2,546 $\times 10^{6}$ to 10,119 $\times 10^{6}$ tons, accounting for 8.1 to 9.2% of the total SOC in the conterminous U.S. This is followed by Minnesota (7.3 to 8.0 %), Florida (5.8 to 6.3%).

Table 1. *Soil carbon in the upper 2 m of each state (region).*

States (Regions)	Area[¶] (km^2)	Organic carbon (SOC)							Inorganic carbon (SIC)						
		Total SOC (10^6 ton)			Content (kg / m^2)				Total SIC (10^4 ton)			Content (kg / m^2)			
		Min[†]	Mid[‡]	Max[#†]	Min	Mid	Max	CV[*]	Min	Mid	Max	Min	Mid	Max	CV
Connecticut	12 406	22	62	133	1.8	5.0	10.7	303	14	84	200	0.0	0.1	0.2	2204
Delaware	5 043	14	49	102	2.7	9.7	20.2	122	0	0	0	0.0	0.0	0.0	
Massachusetts	18 918	36	100	190	1.9	5.3	10.0	220	1	53	130	0.0	0.0	0.1	
Maryland	25 266	49	181	376	1.9	7.2	14.9	125	0	0	0	0.0	0.0	0.0	
Maine	80 584	743	1 022	2 083	9.2	12.7	25.8	179	20	77	156	0.0	0.0	0.0	
New Hampshire	22 801	59	162	323	2.6	7.1	14.2	200	0	8	19	0.0	0.0	0.0	
New Jersey	17 788	95	238	463	5.4	13.4	26.0	188	1	46	112	0.0	0.0	0.1	
New York	118 432	474	1 107	2 101	4.0	9.3	17.7	168	2 167	14 949	34 614	0.2	1.3	2.9	318
Pennsylvania	115 291	177	552	1 128	1.5	4.8	9.8	50	0	321	892	0.0	0.0	0.1	
Rhode Island	2 583	7	16	33	2.6	6.2	12.7	273	0	2	5	0.0	0.0	0.0	
Vermont	23 764	60	156	294	2.5	6.6	12.4	169	263	1 312	2 951	0.1	0.6	1.2	796
West Virginia	61 448	67	220	443	1.1	3.6	7.2	52	53	253	472	0.0	0.0	0.1	
(East)		1 803	3 864	7 669	3.6	7.7	15.2	188	2 519	17 105	39 552	0.0	0.3	0.8	679
Iowa	143 801	1 913	2 870	3 928	13.3	20.0	27.3	76	40 155	167 547	314 494	2.8	11.7	21.9	118
Illinois	143 948	915	1 711	2 639	6.4	11.9	18.3	103	14 881	107 573	222 689	1.0	7.5	15.5	138
Indiana	93 584	589	1 237	2 032	6.3	13.2	21.7	275	35 315	110 555	205 784	3.8	11.8	22.0	123
Michigan	147 532	2 646	3 398	5 515	17.9	23.0	37.4	254	74 387	179 671	318 544	5.0	12.2	21.6	130
Minnesota	209 223	2 535	4 748	8 127	12.1	22.7	38.8	135	96 536	268 396	480 810	4.6	12.8	23.0	131
Missouri	177 484	665	1 376	2 252	3.7	7.8	12.7	94	2 647	21 430	43 203	0.1	1.2	2.4	404
Ohio	105 442	338	745	1 257	3.2	7.1	11.9	168	21 110	65 508	122 811	2.0	6.2	11.6	194
Wisconsin	140 542	1 648	2 790	4 787	11.7	19.8	34.1	247	11 383	55 131	116 697	0.8	3.9	8.3	229
(Midwest)		11 249	18 876	30 538	9.7	16.3	26.3	205	296 413	975 812	1 825 033	2.6	8.4	15.7	160
Arkansas	135 832	340	919	1 666	2.5	6.8	12.3	75	566	4 653	9 739	0.0	0.3	0.7	646
Louisiana	109 273	412	1 478	3 117	3.8	13.5	28.5	136	4 084	17 525	34 661	0.4	1.6	3.2	502
Oklahoma	176 647	581	1 285	2 141	3.3	7.3	12.1	90	30 871	74 969	128 092	1.7	4.2	7.3	352
Texas	660 649	2 546	5 915	10 119	3.9	9.0	15.3	84	744 220	1 689 186	2 875 189	11.3	25.6	43.5	146
(South Central)		3 880	9 597	17 043	3.6	8.9	15.7	102	779 741	1 786 332	3 047 681	7.2	16.5	28.2	194
Alabama	130 948	239	608	1 082	1.8	4.6	8.3	132	199	350	525	0.0	0.0	0.0	
Florida	136 490	1 819	4 103	6 990	13.3	30.1	51.2	251	4 815	8 572	13 161	0.4	0.6	1.0	758
Georgia	149 285	948	2 152	3 620	6.4	14.4	24.2	521	379	1 119	2 002	0.0	0.1	0.1	1081
Kentucky	101 847	194	561	1 053	1.9	5.5	10.3	80	341	1 466	2 726	0.0	0.1	0.3	1273
Mississippi	122 583	177	511	912	1.4	4.2	7.4	171	0	3 411	7 708	0.0	0.3	0.6	427
North Carolina	125 522	782	1 986	3 555	6.2	15.8	28.3	269	0	67	148	0.0	0.0	0.0	
South Carolina	78 489	334	909	1 610	4.3	11.6	20.5	191	513	1 483	2 642	0.1	0.2	0.3	680
Tennessee	104 277	173	508	949	1.7	4.9	9.1	83	3	319	715	0.0	0.0	0.1	
Virginia	102 714	216	631	1 185	2.1	6.1	11.5	334	0	212	468	0.0	0.0	0.0	
(Southeast)		4 883	11 969	20 955	4.6	11.4	19.9	385	6 249	16 998	30 095	0.1	0.2	0.3	1202
Colorado	253 888	621	1 283	2 099	2.4	5.1	8.3	147	44 847	132 329	235 240	1.8	5.2	9.3	202
Kansas	212 325	1 119	2 071	3 152	5.3	9.8	14.8	80	45 150	83 095	126 720	2.1	3.9	6.0	237
Montana	350 837	831	1 758	2 956	2.4	5.0	8.4	104	127 173	269 613	456 712	3.6	7.7	13.0	145
North Dakota	178 589	921	2 058	3 471	5.2	11.5	19.4	74	46 205	126 335	228 106	2.6	7.1	12.8	183
Nebraska	198 419	794	1 595	2 492	4.0	8.0	12.6	88	8 814	49 436	96 233	0.4	2.5	4.9	235
South Dakota	191 914	823	1 738	2 811	4.3	9.1	14.6	88	30 278	86 499	153 930	1.6	4.5	8.0	200
Wyoming	229 275	389	845	1 411	1.7	3.7	6.2	105	49 136	119 395	204 971	2.1	5.2	8.9	186
(Northern Plains)		5 498	11 348	18 391	3.4	7.0	11.4	104	351 601	866 701	1 501 913	2.2	5.4	9.3	190
Arizona	266 867	220	517	906	0.8	1.9	3.4	129	46 578	146 788	274 538	1.7	5.5	10.3	199
California	353 973	758	1 655	2 826	2.1	4.7	8.0	209	10 364	30 016	58 080	0.3	0.8	1.6	602
Idaho	197 155	597	1 212	2 035	3.0	6.1	10.3	123	63 100	143 689	253 610	3.2	7.3	12.9	207
New Mexico	284 358	346	681	1 094	1.2	2.4	3.8	129	105 861	234 631	394 970	3.7	8.3	13.9	256
Nevada	269 415	269	658	1 218	1.0	2.4	4.5	145	32 688	77 987	137 998	1.2	2.9	5.1	314
Oregon	239 876	1 013	2 198	3 778	4.2	9.2	15.7	95	13 774	29 275	48 826	0.6	1.2	2.0	436
Utah	185 030	408	823	1 347	2.2	4.4	7.3	150	147 288	287 997	458 733	8.0	15.6	24.8	174
Washington	161 881	679	1 377	2 285	4.2	8.5	14.1	139	23 368	47 073	75 920	1.4	2.9	4.7	284
(West)		4 289	9 121	15 489	2.2	4.7	7.9	164	443 021	997 455	1 702 675	2.3	5.1	8.7	289

[¶] Soil area reported in STATSGO that excludes water, urban, bare rock, and other non-soil bodies.

[†] Minimum.

[‡] Midpoint.

[#†] Maximum.

[*] Coefficient of variation (%) of soil components in each state (region) with midpoint approach.

California occupies 758 $\times 10^6$ to 2,826 $\times 10^6$ tons of SOC, accounting for 2.4 to 2.6% of the national total SOC. Texas has the greatest SIC with 744,220 $\times 10^4$ to 2,875,189$\times 10^4$ ton (about 35.3 to 39.6%), followed by Utah (about 6.2% with midpoint), Montana and Minnesota (about 5.8%, respectively), and New Mexico (about 5%). California has 10,364 $\times 10^4$ to 58,080 $\times 10^4$ ton (about 0.6 to 0.8 % of the national SIC stock).

Regarding the soil carbon in each USDA-NRCS region, about 27.7 to 35.6% of the U.S. SOC is in the Midwest, 15.5 to 19.0% in the Southeast, 16.7 to 17.5% in the Northern Plains, 12.3 to 15.5% in the South Central, and 13.6 to 14.1% in the West regions (*table 1*). For SIC, about 37.4 to 41.5% of total SIC is in the South Central, 20.9 to 23.6% in the West, 15.8 to 22.4% in the Midwest, and 18.4 to 18.7% in the Northern Plains regions. The East and Southeast regions have little SIC.

Table 2. *Soil carbon in the conterminous United States by soil depth.*

Depth (m)	Organic carbon (SOC)						Inorganic carbon (SIC)					
	Total SOC (10^8 ton)			Content (kg / m^2)			Total SIC (10^8 ton)			Content (kg / m^2)		
	Min[†]	Mid[‡]	Max[#¶]	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
0-0.2	114.44	225.48	367.41	1.55	3.06	4.98	13.65	32.01	55.24	0.19	0.43	0.75
0.2-1.0	139.83	299.46	512.37	1.90	4.06	6.95	81.53	199.59	347.64	1.11	2.71	4.71
1.0-2.0	61.76	122.83	221.08	0.84	1.67	3.00	92.77	234.44	411.82	1.26	3.18	5.58
0-2.0	316.03	647.76	1100.85	4.29	8.78	14.93	187.95	466.04	814.69	2.55	6.32	11.05

[†] Minimum.

[‡] Midpoint.

[#] Maximum.

[¶] Linear correlation coefficient between SOC and SIC content using midpoint approach.

The total SOC and SIC in the top 2 m of the conterminous United States are between 316.03 $\times 10^8$ to 1100.85 $\times 10^8$ tons and 187.95$\times 10^8$ to 814.69 $\times 10^8$ tons, respectively. About one third of the SOC is stored in the 0-0.2 m surface layer and about four-fifths in the top 1 m. For SIC, only about 7% was found in the surface layer, and about 50% was in the top 1 m (*table 2*). The spatial distribution of SOC and SIC in the top 2 m soil layer is presented in Fig. 2. The eastern Great Plains and Midwest have the highest SOC densities. The highest SIC storage is in Texas, Western Plains and the Colorado plateau/great basin. Additionally, the Midwest also has very high SIC in the top 2 m soils.

1.2 Soil Carbon by Soil Order

The SOC and SIC in each soil order of the United States are presented in table 3. SOC in Mollisols accounts for about 31.3 to 37.3% of the total U.S. SOC stock (11,759 $\times 10^6$ to 34,401$\times 10^6$ tons), followed by Histosols (21.5 to 26.9%), and Alfisols (9.4 to11.4%). Considering the SOC content in the top 2 m soils (midpoint approach), Histosols has the highest content (129.4 kg/m^2), followed by Vertisols (12.9 kg/m^2), Mollisols (10.9 kg/m^2) and Andisols (10.1 kg/m^2). SIC is nearly zero in Ultisols and very little in Andisols. Mollisols contains 7,734

$\times 10^6$ to 33,148 $\times 10^6$ tons of SIC, accounting for 40.7 to 41.2% of the national SIC. Aridsols is second (21.3 to 22.6%), followed by Alfisols and Entisols (8.6 to 12.5%, and 9.8 to10.5%, respectively). In the top 2 m soil, Vertisols has the highest SIC at 23.2 kg/m^2 (midpoint value), Aridisols is the second with 12.4 kg/m^2, and Mollisols is the third (9.4 kg/m^2).

In California, SOC in Mollisols accounts for about 29.3 to 29.7% of the total 2m SOC stock (223 $\times 10^6$ to 818 $\times 10^6$ tons), followed by Inceptisols (19.7% to 21.7%), Alfisols (17.4 to18.2%), and Entisols (11.6 to 13.0%). Considering SOC content in each order of California (midpoint), Histosols has the highest content (101.1 kg/m^2), followed by Andisols (13.4 kg/m^2), Ultisols (9.8 kg/m^2), Vertisols (7.8 kg/m^2), Mollisols (7.1 kg/m^2) and Inceptisols (6.1 kg/m^2). SIC in Aridisols accounts for about 64.3 to 71.2% of the total 2 m SIC stocks (616$\times 10^6$ to 3,110 $\times 10^6$ tons), followed by Entisols (8.9% to 17.7%), Vertisols (8.7 to11.1%), and Mollisols (4.6 to 8.5%). Aridisols has the highest content (49.4 kg/m^2), followed by Vertisols (23.3 kg/m^2), Entisols (3.6 kg/m^2), and Mollisols (2.1 kg/m^2).

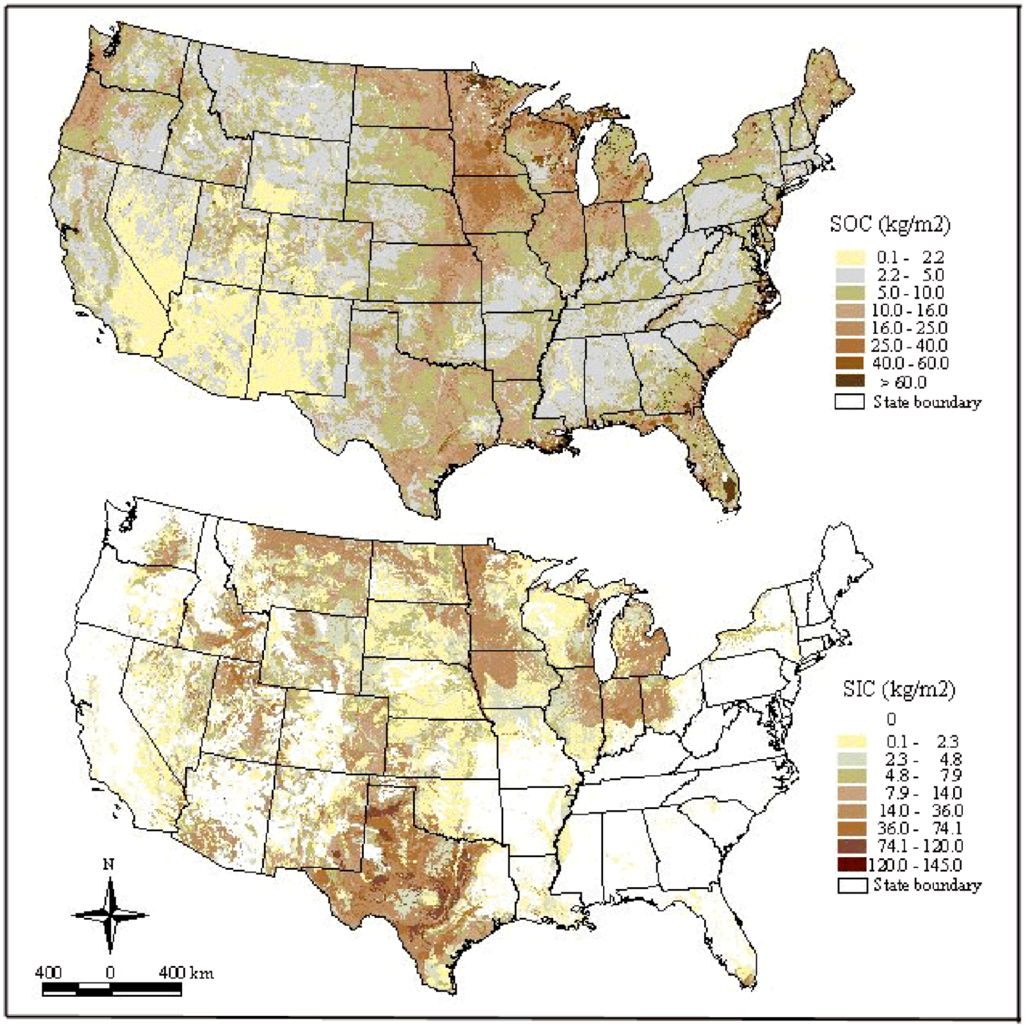


Figure 1. Spatial distribution of SOC and SIC in the top 2 m soils in the conterminous United States (midpoint approach).

Table 3. *Carbon storage and content in the upper 2 m of the soil orders.*

Orders	Area¶ (km^2)	Organic carbon						Inorganic carbon					
		Total storage (10^6 ton)			Content (kg / m^2)			Total storage (10^6 ton)			Content (kg / m^2)		
		Min†	Mid‡	Max#†	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
Alfisols	1 274 102	2 968	7 241	12 530	2.3	5.7	9.8	1 621	5 399	10 192	1.3	4.2	8.0
Andisols	68 666	323	694	1 204	4.7	10.1	17.5	1	2	3	0.0	0.0	0.0
Aridisols	809 423	964	2 283	3 992	1.2	2.8	4.9	4 243	10 025	17 376	5.2	12.4	21.5
Entisols	1 054 015	1 932	4 996	9 026	1.8	4.7	8.6	1 849	4 867	8 536	1.8	4.6	8.1
Histosols	107 249	8 490	13 883	23 911	79.2	129.4	223.0	62	259	533	0.6	2.4	5.0
Inceptisols	787 254	2 038	5 172	9 459	2.6	6.6	12.0	1 875	3 834	6 320	2.4	4.9	8.0
Mollisols	2 020 694	11 759	21 994	34 401	5.8	10.9	17.0	7 734	18 990	33 148	3.8	9.4	16.4
Spodosols	250 133	714	1 999	3 830	2.9	8.0	15.3	50	149	282	0.2	0.6	1.1
Ultisols	860 170	1 675	4 741	8 750	1.9	5.5	10.2	0	0	0	0.0	0.0	0.0
Vertisols	132 433	708	1 714	2 886	5.3	12.9	21.8	1 360	3 075	5 072	10.3	23.2	38.3

¶ Soil area with taxonomic information reported in STATSGO

† Minimum

‡ Midpoint

\# Maximum

Calculating SOC based on soil taxonomy and ecosystems are two common approaches for estimating SOC pools at the national and world scale. In the present study, results obtained based on the analysis of 111,247 soil components in the conterminous United States of STASTO suggests that predicting the SOC pool for the U.S. using a taxonomy-based method will have a higher accuracy than methods based on land resource regions (or ecosystems) since the coefficient of variation for SOC in the orders is much smaller than that in land resource regions.

Factors Controlling Soil Carbon in California and the Conterminous United States

2.1 Soil Carbon Storage vs. Terrestrial Ecosystem and Land-use

For any of the three depths examined, forests contain the greatest national SOC stock (*table 4*). However, the relative amount contained in the forests decreases as soil depth increases. The forest ecosystem contributes 30.4%, 27.7%, and 26.9%, respectively, to the upper 0.2 m, 1 m, and 2 m national SOC stocks. The decline in relative C storage with depth is also observed in grass and shrub natural ecosystems. Agricultural land is the second largest contributor to national SOC stock at any depth considered. In the agriculture ecosystem, the percentage SOC in each soil layer is similar. They are 25.2%, 25.7%, and 25.3% of the national total in the upper 0.2 m, 1 m and 2 m, respectively. The ratios between SOC sequestrated in top 0.2 m layer and that in the top 2 m layer by ecosystem are 38.6%, 38.5%, 39.3%, 36.5%, 34.7%, and 21.8% in the shrub, grass, forest, cultivated pasture, agriculture, and wetland, respectively, reflecting the fact that agriculture ecosystems have generally experienced a loss of labile SOC in the surface layer as a result of cultivation. The pattern of SIC by the ecosystems is different from that of SOC. Shrub ecosystem has the greatest SIC stocks in the top 0.2 m (44.3%) and 1m (31.2%) layers. However, for the 2 m layer, the greatest SIC pool (29.1%) is found in agricultural ecosystems followed by shrub (26.9%), grass (22.5%), cultivated pasture (9.2%), forest (8.8%), and wetland (2.5%) ecosystems. A trend similar to that for SOC exists in SIC stocks of the ecosystems: the amount contained in natural ecosystems decreases, while the amount contained in managed ecosystems increases, as soil depth increases. The ratios between SIC sequestrated in the surface layer (0.2m) and that in the top 2 m layer by ecosystem type are 11.3%, 8.0%, 8.2%, 4.7%, 3.2%, and 5.2%, respectively in the shrub, grass, forest, pasture, agriculture, and wetlands. The SIC ratios between 1 m and 2 m soil layers are 57.8%, 54.4%, 50.7%, 43.4%, 40.7%, and 49.6%, respectively for the same sequence of the ecosystem types. The managed ecosystems have the lowest ratios of SIC existing in the upper soil.

***Table 4**. Soil carbon by terrestrial ecosystems in the conterminous United States.*

Depth (m)	Terrestrial Ecosystem	Area[¶] (×10^4 km^2)	Organic carbon				Inorganic carbon			
			Min[†]	Mid[‡]	Max[#]	%[*]	Min	Mid	Max	%
0 – 0.2	Agriculture	132.6	326	568	857	25.2	15	43	75	13.4
	Forest	228.1	314	686	1 183	30.4	15	33	58	10.4
	Grass	124.8	153	291	461	12.9	36	83	143	26.1
	Pasture	72.9	129	248	396	11.0	8	20	35	6.3
	Shrub	142.6	107	208	349	9.2	63	142	247	44.3
	Wetland	31.5	90	201	348	8.9	3	6	10	1.9
	Total[**]	737.4	1 144	2 255	3 674	100.0	137	320	552	100.0
0 –1.0	Agriculture	132.6	733	1 351	2 093	25.7	208	552	972	23.9
	Forest	228.1	650	1 453	2 572	27.7	85	208	372	9.0
	Grass	124.8	305	632	1 033	12.0	247	571	973	24.6
	Pasture	72.9	270	552	905	10.5	75	187	324	8.1
	Shrub	142.6	207	446	768	8.5	306	723	1 265	31.2
	Wetland	31.5	306	665	1 177	12.7	20	58	105	2.5
	Total	737.4	2 543	5 249	8 798	100.0	952	2 316	4 029	100.0
0 – 2.0	Agriculture	132.6	862	1 639	2 587	25.3	516	1 357	2 390	29.1
	Forest	228.1	821	1 745	3 123	26.9	159	410	738	8.8
	Grass	124.8	350	756	1 255	11.7	453	1 048	1 788	22.5
	Pasture	72.9	321	680	1 136	10.5	166	430	756	9.2
	Shrub	142.6	241	540	941	8.3	524	1 251	2 190	26.9
	Wetland	31.5	470	924	1 640	14.3	40	117	215	2.5
	Total	737.4	3 160	6 478	11 009	100.0	1 880	4 660	8 147	100.0

[¶] Area calculated after overlaying NLCD with STATSGO.

[†] Minimum

[‡] Midpoint

[#] Maximum

[*] Percentage in midpoint approach

[**] Total soil area in the conterminous United States excludes water, urban, bare rock, and other non-soil bodies.

In California, SOC in the top 2 m soil layer is estimated as 41.1%, 10.5%, 17.9%, 22.9%, 5.7%, and 2.0% in forest, agriculture, grass, shrub, cultivated pasture, and wetland ecosystems, respectively. The SOC ratios between the 0.2 m and 2 m soil layers are 53.3% in forest, 38.0% in agriculture, 50.5% in grass, 52.6% in shrub, 41.8% in cultivated pasture, and 28.2% in wetland. SIC in the top 2 m soils are 80.3% in shrub ecosystem, 8.9% in grass, and 4.8% in agricultural lands. The ratios 0.2m / 2m ratio of SIC are 9.9%, 6.1%, 11.1%, 8.7%, 7.5%, and 9.6% in the forest, agriculture, grass, shrub, cultivated pasture, and wetland ecosystems, respectively, while for the ratios between 1 m and 2 m layers are 66.7%, 52.8%, 61.5%, 63.3%, 50.8%, and 59.7%, respectively.

2.2. Topographic Effects on Soil Carbon

The total SOC and SIC in different elevation zones of the conterminous U.S. is shown in table 5. Most of the SOC (75.3%) and about half of the SIC (49.7%) are sequestrated below 600 m in elevation. The SOC and SIC densities in each elevation zones are presented in figure 2. There is a decrease in SOC densities as elevation increases, and those elevation zones lower than 600 m have the greatest SOC densities in the conterminous U.S. The portion of SOC sequestrated in the surface layer by elevation is 28.4%, 34.1%, 38.0%, 42.3%, 40.1%, 38.8%, 39.7%, and 46.3% in the <200 m, 200-400 m, 400-600 m, 600-800 m, 800-1000 m, 1000-1200 m, 1200-1400 m, and >1400 m elevation zones, respectively, showing an increasing trend of SOC in the surface layer of soils. There was no obvious pattern of SIC densities with change of elevation.

The total SOC and SIC in each slope class is presented in table 6. Almost four-fifths of both SOC (78.4%) and SIC (79.4%) in the U.S. are sequestrated in relatively flat areas. SOC and SIC content in each slope class are shown in figure 2. The SOC content in flat terrain is almost twice as much as that in other slope classes. The SOC ratios between the surface layer and the top 2 m soil layer (0.2 m/ 2m) are 32.0%, 43.6%, 47.5%, 48.0%, 47.7%, 48.1%, 50.2%, and 55.3% in the <1°, 1-2°, 2-3°, 3-4°, 4-5°, 5-10°, 10-20°, and 20-30° slope classes, respectively. There is a trend of a greater portion of SOC in the surface layer as slope increases. The effect of slope on SIC is more obvious than that on SOC, and there is a decrease in SIC densities as the slope becomes steeper.

Table 5. *Soil carbon by elevation zones in the conterminous United States.*

Elevation zone (100m)	Area ($\times 10^4$ km^2)¶	Organic carbon (10^7 ton)				Inorganic carbon (10^7 ton)			
		Min†	Mid‡	Max#	%*	Min	Mid	Max	%
<2	169.8	883	2040	3579	31.1	204	559	996	11.6
[2-4)	169.0	1138	2044	3360	31.2	462	1272	2291	26.5
[4-6)	81.4	431	851	1454	13.0	222	556	973	11.6
[6-8)	54.6	151	351	613	5.4	163	385	667	8.0
[8-10)	43.3	107	235	397	3.6	182	405	685	8.4
[10-12)	35.5	85	188	316	2.9	151	346	591	7.2
[12-14)	42.9	90	196	334	3.0	216	478	798	10.0
>=14	168.2	308	651	1107	9.9	350	801	1383	16.7

¶ Area calculated after overlaying NLCD with STATSGO.

† Minimum

‡ Midpoint

Maximum

* Percentage of midpoint value

Table 6. *Soil carbon by slope classes in the conterminous United States.*

Slope class (Degree)	Area[¶] (×10^4 km^2)	Organic carbon (10^7 ton)				Inorganic carbon (10^7 ton)			
		Min[†]	Mid[‡]	Max[#]	%[*]	Min	Mid	Max	%
<1	484.8	2550	5140	8645	78.4	1530	3821	6661	79.4
[1-2)	109.3	265	572	1005	8.7	246	575	993	11.9
[2-3)	47.2	99	223	398	3.4	71	166	290	3.4
[3-4)	30.2	64	143	256	2.2	35	81	145	1.7
[4-5)	21.9	48	107	190	1.6	21	49	89	1.0
[5-10)	54.2	123	274	487	4.2	40	97	180	2.0
[10-20)	18.7	43	95	170	1.5	9	25	50	0.5
[20-30)	1.0	2	5	9	0.1	0	1	1	0.0

[¶] Area calculated after overlaying NLCD with STATSGO.

[†] Minimum

[‡] Midpoint

[#] Maximum

[*] Percentage of midpoint value.

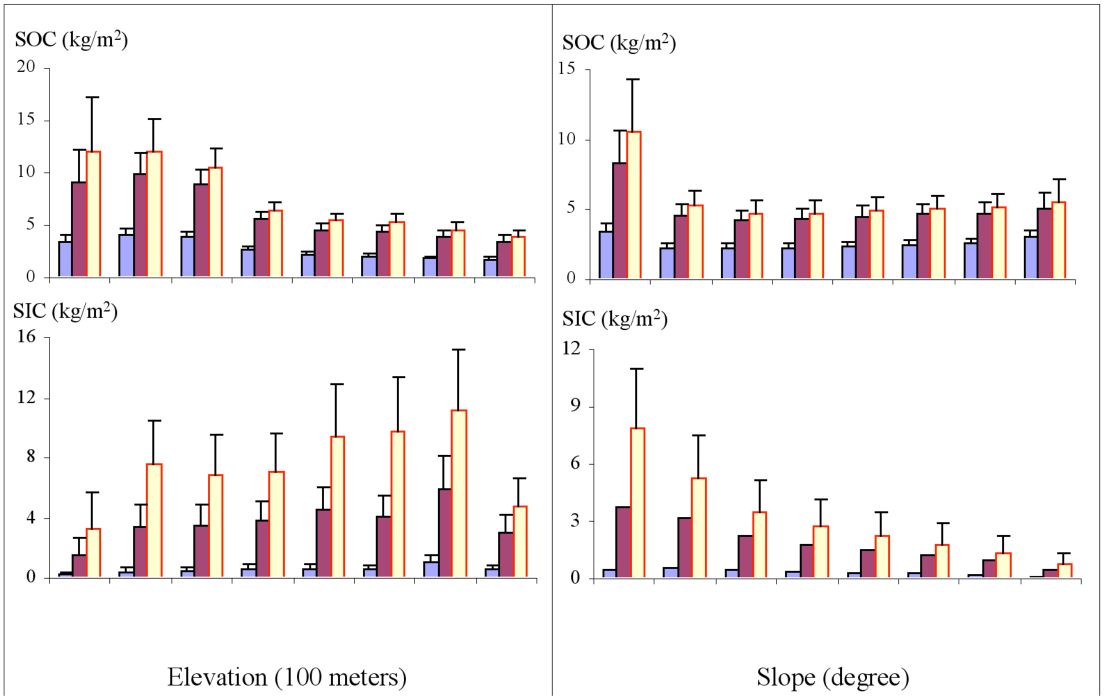


Figure 2. Soil organic and inorganic carbon densities in each elevation zone and slope class.

Table 7. *Soil carbon by elevation zones and slope classes in California.*

Elevation					Slope				
Zones (100m)	SOC		SIC		Classes (Degree)	SOC		SIC	
	%*	Kg/m^2	%*	Kg/m^2		%*	Kg/m^2	%*	Kg/m^2
<2	29.6	5.9	24.1	0.9	<1	31.1	5.1	35.6	1.1
[2-4)	9.2	3.5	29.9	2.1	[1-2)	11.8	3.7	28.1	1.6
[4-6)	7.8	3.4	17.3	1.4	[2-3)	9.9	3.9	13.3	1.0
[6-8)	7.3	3.1	8.8	0.7	[3-4)	8.3	4.1	7.6	0.7
[8-10)	6.9	3.4	5.1	0.5	[4-5)	7.0	4.3	4.5	0.5
[10-12)	6.4	4.2	3.2	0.4	[5-10)	21.6	4.5	8.3	0.3
[12-14)	7.9	5.1	6.1	0.7	[10-20)	9.8	4.8	2.5	0.2
>=14	25.0	5.1	5.5	0.2	[20-30)	0.5	4.8	0.1	0.2

* Percentage of soil carbon by midpoint value.

In California, 46.5% SOC and 71.3% SIC are sequestrated below 600 m in elevation. The greatest SOC densities are in the lowest elevation zone. SOC content decreases as elevation increases until about 600-800 m in elevation after which SOC increases again as elevation increases further. In terms of SOC in slope classes, 31.1% SOC and 35.6% SIC are in areas of flat landscape. 89.7% SOC and 97.4% SIC are in areas whose slopes are less than 10°. SIC content decreases obviously as slope increases (*table 7*).

2.3. Climate effects on soil carbon

The total SOC and SIC in each MAP zone are estimated in table 8. It is obvious that most SOC is sequestrated in the zones having adequate precipitation. Areas with less than 400 mm MAP, covering 25.4% of the conterminous U.S., have only 10.1% of the total SOC. In contrast, low SIC is located in high precipitation zones. Only 4.8% of the total SIC in the U.S. is located in the > 1,000 mm MAP zones. Although SIC indeed occurs in arid and semiarid regions as might be expected, there is also a large portion of SIC in areas of moderate MAP. The SOC and SIC densities by MAP zone are shown in figure 3. SOC content increases as MAP increases until 700-850 mm, then, SOC content fluctuates as MAP continues to increase, a pattern consistent with that observed in Central Plains grasslands by Burke et al. (1989). There is no obvious pattern of SIC content versus MAP until MAP exceeds 1,000 mm, at which point and after SIC drops dramatically. A positive linear correlation between SOC and SIC was found in the lower MAP zones, especially in the lower layer between 1 m and 2 m deep of the soil (*table 8*). The positive relationship between SOC and SIC drops dramatically as MAP increases.

***Table 8.** Soil carbon precipitation zones in the conterminous United States.*

Precipitation (10mm)	Area (×10^4 km^2)	Organic carbon (10^7 ton)				Inorganic carbon (10^7 ton)				r¶
		Min†	Mid‡	Max#†	%*	Min	Mid	Max†	%	
< 10	3	1	3	6	0.0	4	13	26	0.3	0.637
[10-25)	58	48	122	225	1.8	221	482	807	10.0	0.403
[25-40)	135	257	552	924	8.3	497	1146	1967	23.7	0.355
[40-55)	112	383	808	1336	12.2	412	990	1714	20.5	0.268
[55-70)	69	346	679	1137	10.2	273	689	1209	14.2	0.217
[70-85)	74	715	1175	1915	17.7	273	712	1268	14.7	0.007
[85-100)	77	488	911	1464	13.7	205	580	1047	12.0	0.075
[100-115)	80	258	584	1064	8.8	56	163	297	3.4	0.014
[115-130)	70	314	757	1344	11.4	8	27	52	0.6	0.013
>=1300	95	421	1058	1915	15.9	11	37	71	0.8	0.003

† Minimum
‡ Midpoint
# Maximum
* Percentage of midpoint value
¶ Linear correlation coefficient between SOC and SIC in 1-2 m soil layer.

***Table 9.** Soil carbon by temperature zones in the conterminous United States.*

Temperature (°C)	Area¶ (×10^4 km^2)	Organic carbon (10^7 ton)				Inorganic carbon (10^7 ton)			
		Min†	Mid‡	Max#†	%*	Min	Mid	Max	%
< 0	6	16	32	55	0.5	1	5	13	0.1
[0-3)	17	66	137	249	2.1	18	50	100	1.0
[3-6)	100	651	1132	1998	16.9	227	577	1032	11.6
[6-9)	176	810	1518	2463	22.7	385	998	1766	20.1
[9-12)	152	570	1141	1852	17.0	360	933	1620	18.8
[12-15)	113	292	682	1178	10.2	220	515	878	10.4
[15-18)	142	357	863	1500	12.9	392	933	1617	18.8
[18-21)	65	305	781	1419	11.7	323	714	1213	14.4
>=21	24	183	405	687	6.1	72	234	443	4.7

¶ Area calculated after overlaying NLCD with STATSGO. † Minimum ‡ Midpoint # Maximum * Percentage of midpoint value

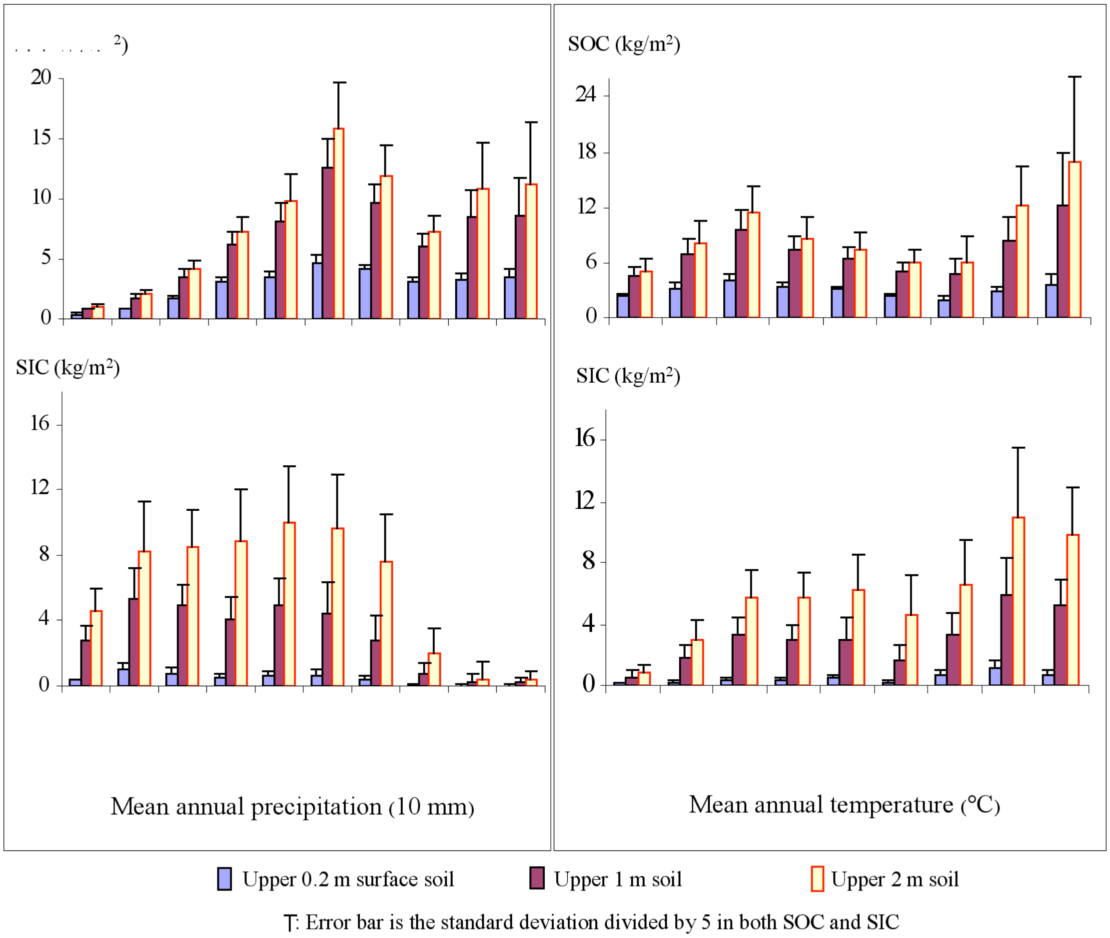
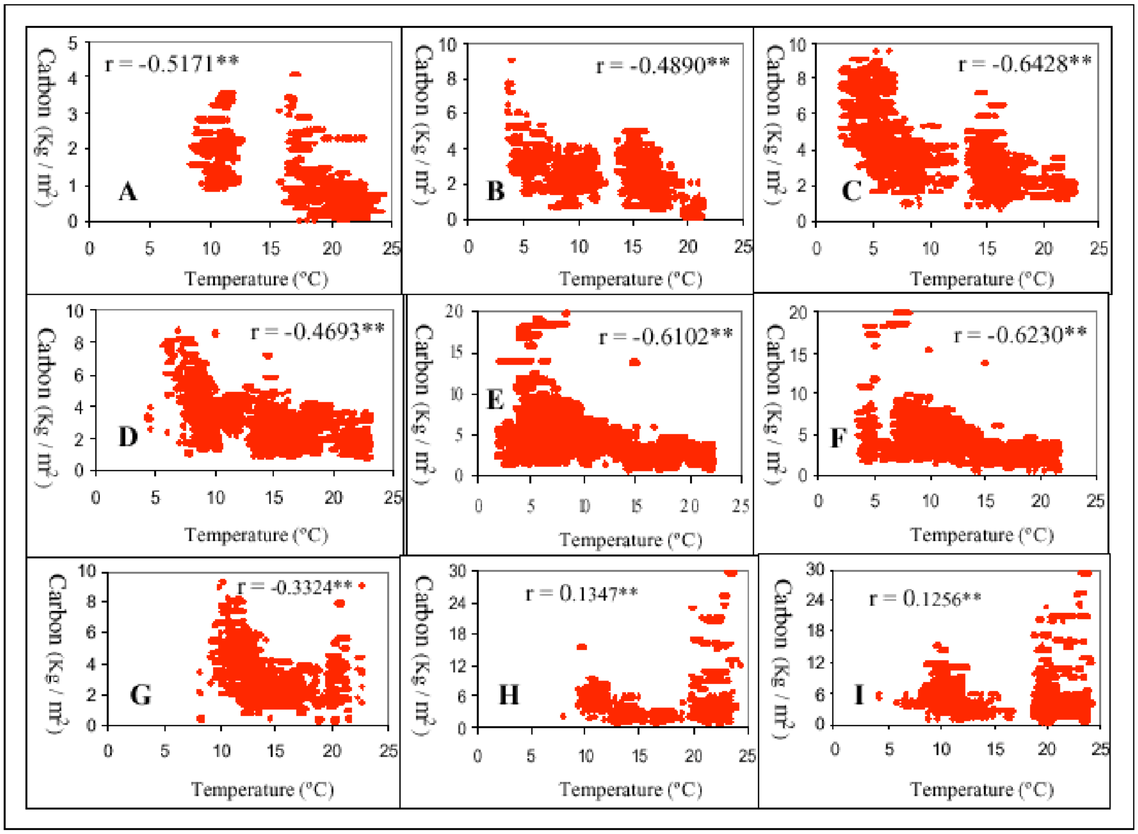


Figure 3. Soil organic and inorganic carbon densities (midpoint value) in each precipitation and temperature zone.

Only 0.5% SOC was sequestrated in the lower than 0 °C MAT zone (*table 9*). Most (56.6%) SOC is located in the 3-12 °C MAT zones. The SOC and SIC densities in MAT zones are presented in figure 3. A non-linear relationship between SOC and MAT was observed, indicating that the effect of temperature on SOC is not as obvious as that of the other factors studied.

Within each MAP zone, the relationship between SOC and MAT is further examined in grass and forest ecosystems given flat topography in lower than 600 m elevation. The SOC (kg/m^2) versus MAT for the top 0.2 m of grassland is presented in figure 4. There is clearly a negative correlation between SOC and MAT in all MAP zones with less than 1,150 mm. The correlation patterns of SOC and MAT for the top 1 m grassland or all three depths of forestland are similar and they are similar to that in the top 0.2 m of grassland. The relationship between SOC and MAT was further explored with linear and exponential regression. A total of 78% of the pairs of datasets in each MAP zone of a given land cover fit an exponential model better than a linear model, which matches the type of the function widely used to describe the response of SOC decomposition versus MAT. SOC is more sensitive in the surface layer than that in the deeper layers. Within each MAP zone, the means of SOC (kg/m^2) were averaged at every 0.1 ºC for the surface layer of grassland. The empirical relationships between the mean SOC and MAT are presented in figure 5. In grassland soils, the response of the mean SOC to temperature varies with MAP, and the sensitivity (speed of decrease) of SOC to increasing temperature decreases as MAP increases. When MAP passes 1,000 mm, the response of mean SOC to MAT gradually changes from monotonously decrease to polynomial (*fig. 5*). SOC is less sensitive to increasing temperature in forests than that in grassland. However, it should be noted that our result only depicts the soils below “O” horizons. Litter or “O” horizons excluded from STATSGO store a substantial amount of carbon in many forests. A more sensitive response of SOC to MAT than that reported in this study is anticipated in some forests when “O” horizons are considered.



A: <250 mm MAP zone. **B:** [250-400) mm MAP zone. **C:** [400-550) mm MAP zone.

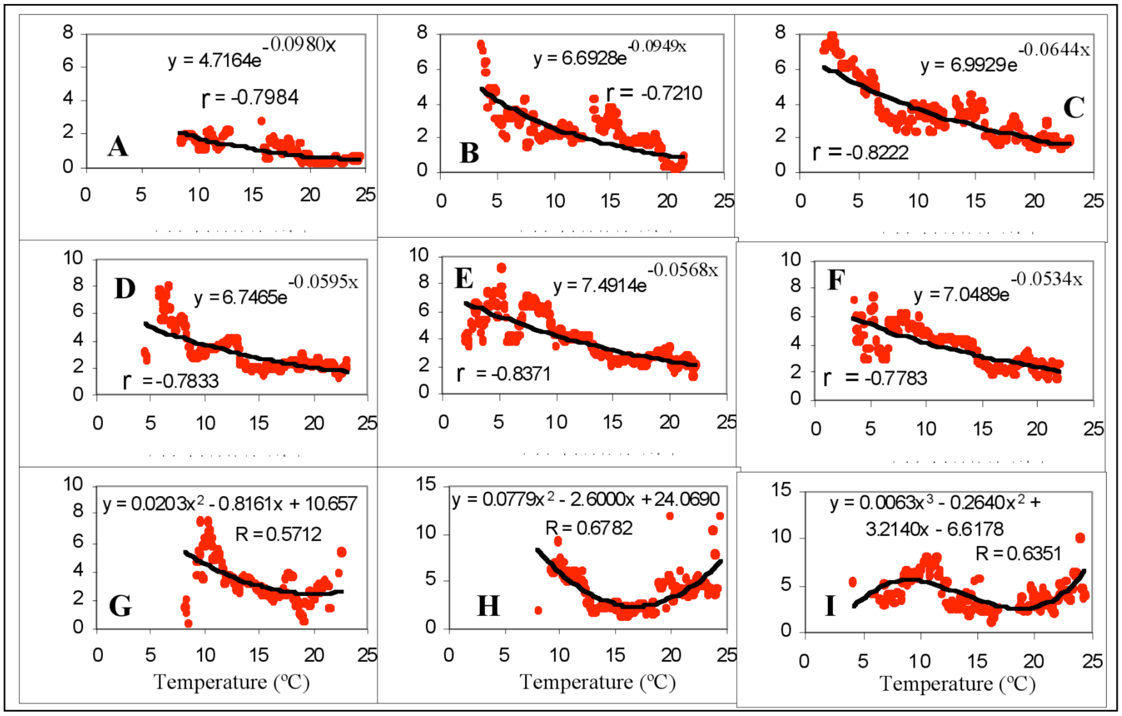
D: [550-700) mm MAP zone. **E:** [700-850) mm MAP zone. **F:** [850-1000) mm MAP zone.

G: [1000-1150) mm MAP zone. **H:** [1150-1300) mm MAP zone. **I:** >=1300 mm MAP zone.

r: Linear correlation coefficient **: Significant at 0.01 probability level

Figure 4. SOC response to the Mean Annual Temperature (MAT) in 0-0.2m surface of grassland.

In California, 50.6% of total SOC exists in arid or semiarid land since 64.4% land in California has less than 550 mm MAP. However, it is obvious that SOC content increases as MAP increases (*table 10*). 82.5% of total SIC locates in arid land. SIC content decreases dramatically as MAP increases. In terms of SOC or SIC content vs. MAT in California, it is obvious that SOC content decreases while SIC content increases as MAT increases.



● Carbon (kg/m^2) in 0.2 m surface of grass land averaged at every 0.1 °C. —— Exponential or polynomial trend line.

r: Linear correlation coefficient between x and ln(y) in exponential model.

R: Multiple correlation coefficient in polynomial model.

A: <25 mm MAP zone.
B: [250-400) mm MAP zone.
C: [400-550) mm MAP zone.
D: [550-700) mm MAP zone.
E: [700-850) mm MAP zone.
F: [850-1000) mm MAP zone.
G: [1000-1150) mm MAP zone.
H: [1150-1300) mm MAP zone.
I: >=1300 mm MAP zone.

Figure 5. Mean soil organic carbon (kg/m^2) response to mean annual temperature in the top 0.2m of grassland soil.

Geographical Patterns of Soil Carbon Residence Times in California and USA

The geographical patterns of C, and the GIS-based approach we took, are amenable to a simple, but nonetheless useful, analysis of soil C cycling. As a first step, we linked the soil C patterns with climate-driven estimates of soil respiration (Raich and Schlesinger 1992; Raich and Potter 1995) to establish single pool, first order decay model-based estimates of soil C residence times (*fig. 6*). While single pool models have numerous weaknesses (especially ignoring the importance of fast cycling C (Davidson et al. 2000), the approach provides important first-order constraints on the response of soil C pools to climate change (Jenkinson et al. 1991; Amundson 2001). Our results showed that the geographical patterns of soil carbon and carbon residence times are very similar (*fig. 1 and 6*), indicating that the higher content of carbon in the United States are partially resulted from longer residence time or a slower decomposition rate driven by the climate. In California, soil carbon with the longest residence times is around the Bay area.

Table 10. *Soil carbon by precipitation and temperature zones in California.*

Precipitation					Temperature				
Zones (10mm)	SOC		SIC		Zones (Degree)	SOC		SIC	
	%*	Kg/m^2	%*	Kg/m^2		%*	Kg/m^2	%*	Kg/m^2
< 10	1.0	1.1	18.4	36.1	< 0	1.4	7.8	0.0	0.0
[10-25)	10.0	1.5	64.1	17.1	[0-3)	1.1	7.1	0.0	0.0
[25-40)	18.8	5.3	8.9	4.6	[3-6)	4.3	6.2	0.0	0.1
[40-55)	20.8	6.2	6.6	3.6	[6-9)	13.3	5.6	3.2	2.0
[55-70)	9.5	5.3	1.3	1.3	[9-12)	18.2	6.3	3.8	2.0
[70-85)	5.9	5.3	0.2	0.3	[12-15)	24.5	5.2	6.5	2.1
[85-100)	6.2	6.0	0.1	0.1	[15-18)	32.9	4.4	20.1	4.0
[100-115)	6.5	6.3	0.0	0.1	[18-21)	2.4	1.3	19.4	15.2
[115-130)	5.4	6.5	0.1	0.1	>=21	1.8	1.1	47.0	42.2
>=1300	15.9	6.9	0.3	0.2					

* Percentage of midpoint value.

Incorporate CENTURY Soil C Models into a GIS-based Framework to Simulate Soil Carbon Response to Environmental Change in California

A GIS shell in Arcview GIS created with Avenue language was developed for CENTURY (a point soil carbon model generated by Natural Resource Ecology Laboratory, Colorado State University) to simulate soil carbon under three natural ecosystems (grass, forest, shrub) of California (*fig. 7*). Soil carbon under eight land-cover types of the three ecosystems (C3 Grasslands, Temperate Coniferous Savanna, Maritime Coniferous Forest, Continental Coniferous Forest, Warm Temperate/Subtropical Mixed Forest, Mediterranean Shrubland, Temperate Arid Shrubland, Subtropical Arid Shrubland) can be simulated. Simulation can be conducted for a single polygon of STATSGO or the entire ecosystem (NLCD of California as a background).

More than 600 input parameters were required by CENTURY model to simulate soil carbon for a certain ecosystem with a certain management. The shell has two options: default schedule file or changed schedule file. Default schedule file option uses the schedule files in literature (VEMAP, 1995, Global biogeochemical cycles 9: 407-437) for each land-cover by updating necessary input parameters of each polygon of STATSGO in California. Selecting 'changed schedule file' option, a user can change schedule file to simulate soil carbon under any management systems and any time period (CENTURY User's Manual). More than 400 output parameters will be generated by CENTURY. The shell only extracts five output results (g/m2) of the simulation: SOM1C_1(carbon in surface microbe pool); SOM1C_2 (carbon in active soil organic matter); SOM2C (carbon in slow pool soil organic matter); SOM3C (carbon in passive soil organic matter); and SOMTC (total soil carbon including belowground structural and metabolic) and shows them both in table and in map format. All the other output results are kept in result.bin file and can be extracted by list.100 file, the same way as in the original CENTURY model (CENTURY User's Manual). With 'default schedule file' option, the simulation result of soil carbon for 'Continental Coniferous Forest' land-cover (simulation based on a single polygon of STATSGO or the entire ecosystem) in 100 years were present in figure 8. This GIS shell can be used to simulate soil carbon dynamics as a response to climate or management change in California by CENTURY model, which will give people the ability to test the model on a regional to national scale.

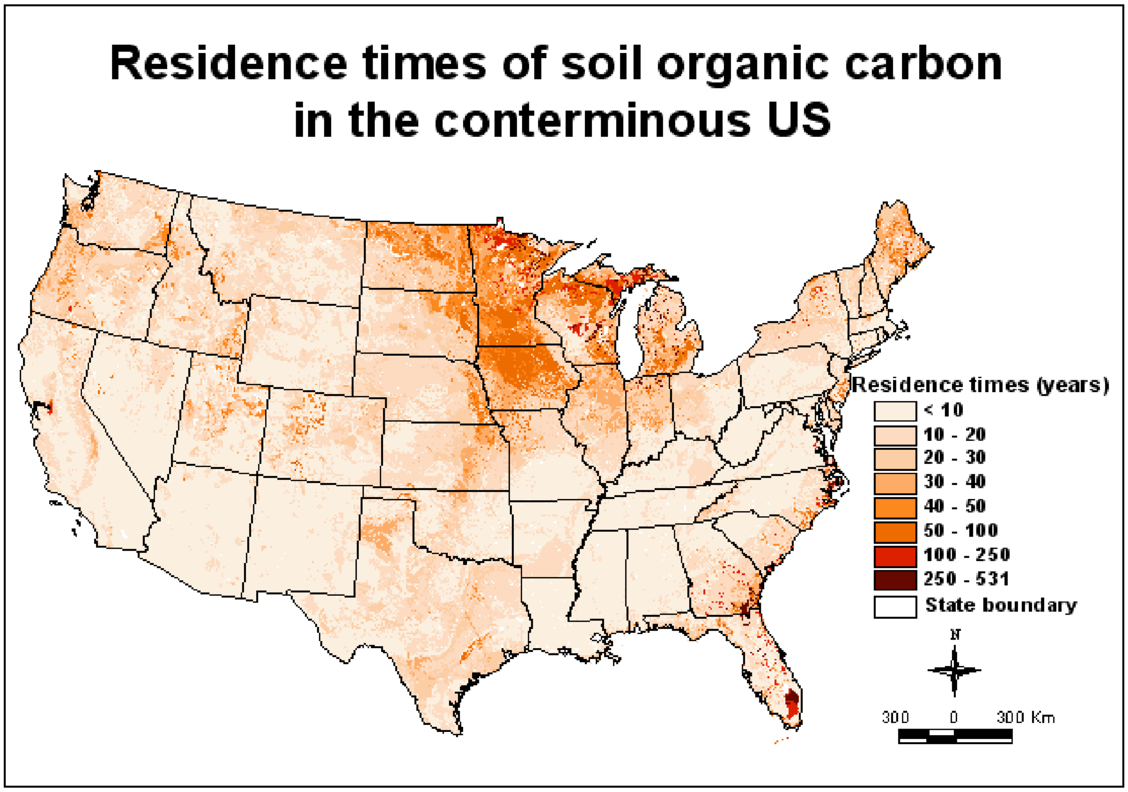
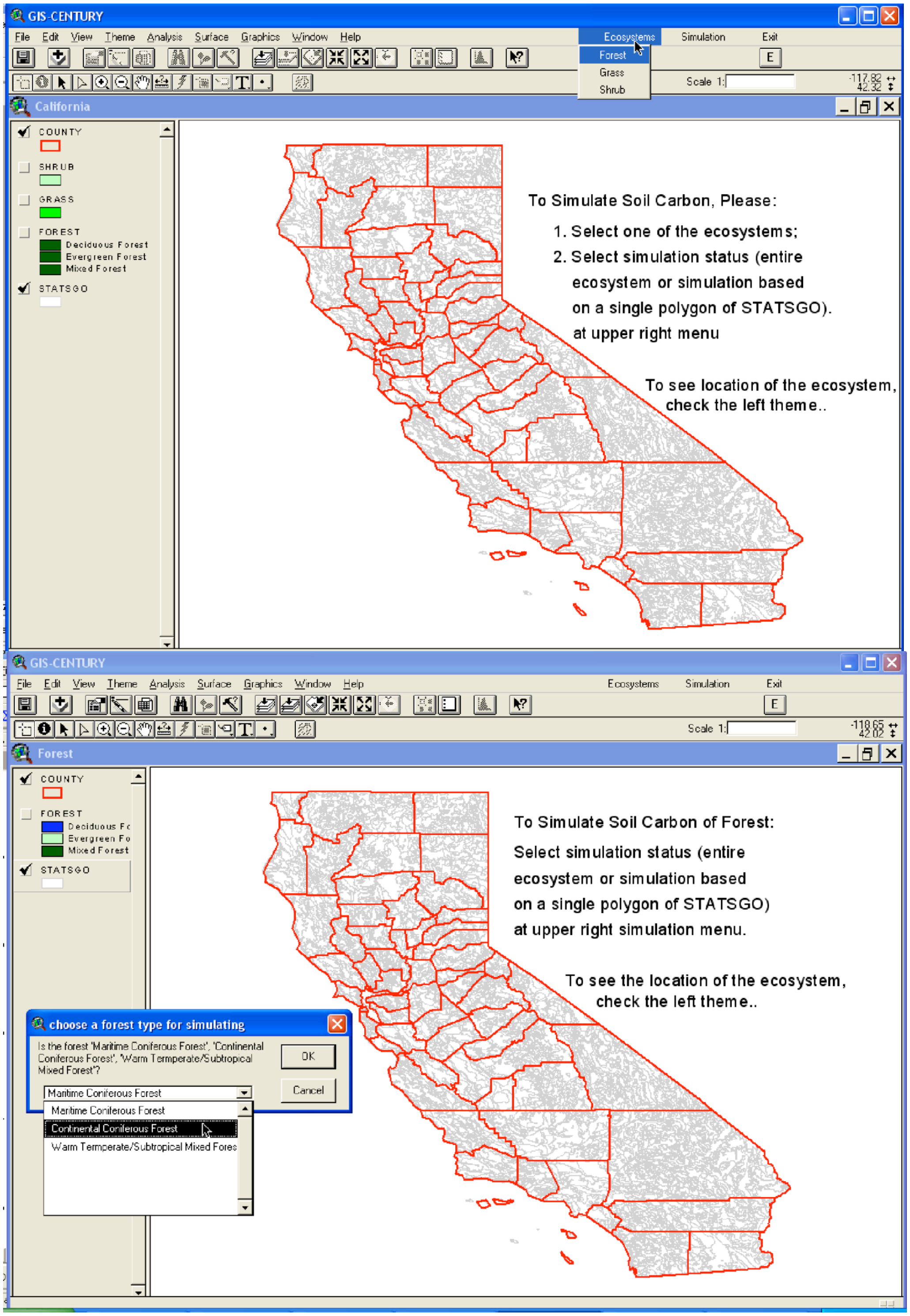


Figure 6. Soil organic carbon (SOC) residence times in the conterminous United States.

Discussion

It is commonly assumed that most of SIC occurs in soils of arid and semi-arid regions (Grossman et al. 1995; Schlesinger 1997; Ral et al. 1998b; Monger and Martinez-Rios 2000), a pattern observed here for the upper 1m. However, when SIC in the 2 m soil is considered, a huge SIC pool was also found in the Midwest, in which mean annual precipitation (MAP) is about 700 to 1,000 mm. While the SIC in the upper 1 m is generally leached out in these climates (Jenny and Leonard 1936), the deeper depth still retains parent material carbonates. In the Midwest, the SIC (2 m) strongly reflects the extent of the last glaciation (Paul et al. 1998).



To Simulate Soil Carbon, Please:

1. Select one of the ecosystems;
2. Select simulation status (entire ecosystem or simulation based on a single polygon of STATSGO). at upper right menu

To see location of the ecosystem, check the left theme..

To Simulate Soil Carbon of Forest:

Select simulation status (entire ecosystem or simulation based on a single polygon of STATSGO) at upper right simulation menu.

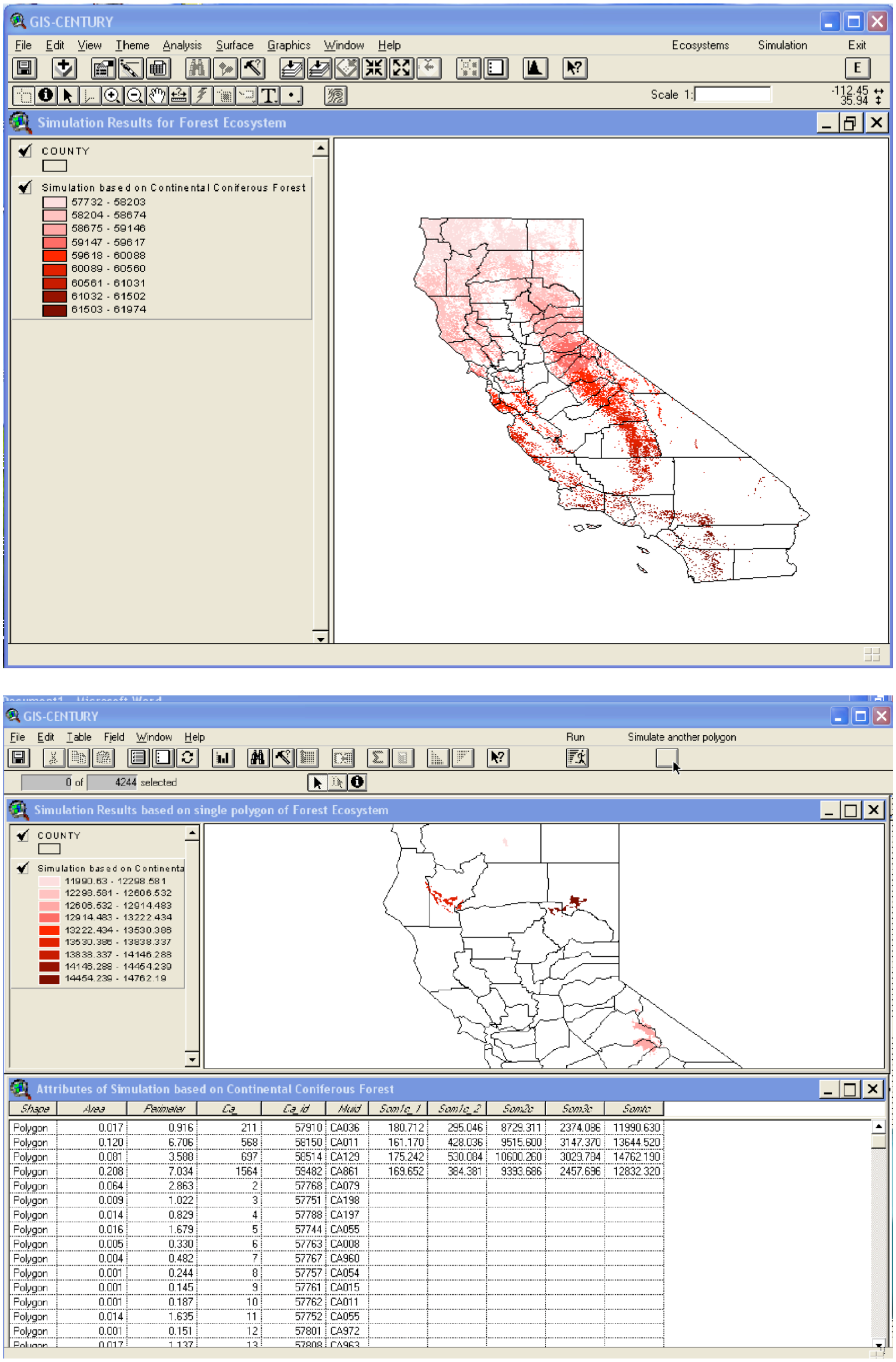
To see the location of the ecosystem, check the left theme..

Is the forest 'Maritime Coniferous Forest', 'Continental Coniferous Forest', 'Warm Termperate/Subtropical Mixed Forest'?

Maritime Coniferous Forest

- Maritime Coniferous Forest
- Continental Coniferous Forest
- Warm Termperate/Subtropical Mixed Fores

Figure 7. A 'CENTURY' GIS shell for soil carbon simulation under grass, forest, and shrub ecosystems.



Shape	Area	Perimeter	Ca_	Ca_id	Muid	Som1c_1	Som1c_2	Som2c	Som3c	Somtc
Polygon	0.017	0.916	211	57910	CA036	180.712	295.046	8729.311	2374.086	11990.630
Polygon	0.120	6.706	568	58150	CA011	161.170	428.036	9515.600	3147.370	13644.520
Polygon	0.081	3.588	697	58514	CA129	175.242	530.084	10600.260	3029.784	14762.190
Polygon	0.208	7.034	1564	59482	CA861	169.652	384.381	9393.686	2457.696	12832.320
Polygon	0.064	2.863	2	57768	CA079					
Polygon	0.009	1.022	3	57751	CA198					
Polygon	0.014	0.829	4	57788	CA197					
Polygon	0.016	1.679	5	57744	CA055					
Polygon	0.005	0.330	6	57763	CA008					
Polygon	0.004	0.482	7	57767	CA960					
Polygon	0.001	0.244	8	57757	CA054					
Polygon	0.001	0.145	9	57761	CA015					
Polygon	0.001	0.187	10	57762	CA011					
Polygon	0.014	1.635	11	57752	CA055					
Polygon	0.001	0.151	12	57801	CA972					
Polygon	0.017	1.137	13	57808	CA963					

Figure 8. Simulation results for ‘Continental Coniferous Forest’ land cover in a 100-year period.

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