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Valuation of Soil Organic Carbon Stocks in the Contiguous United States Based on the Avoided Social Cost of Carbon Emissions

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Abstract: Soil organic carbon (SOC) generates several ecosystem services (ES), including a regulating service by sequestering carbon (C) as SOC. This ES can be valued based on the avoided social cost of carbon (SC-CO_2) from the long-term damage resulting from emissions of carbon dioxide (CO_2). The objective of this study was to assess the value of SOC stocks, based on the avoided SC-CO_2 ($42 per metric ton of CO_2 in 2007 U.S. dollars), in the contiguous United States (U.S.) by soil order, soil depth (0–20, 20–100, 100–200 cm), land resource region (LRR), state, and region using information from the State Soil Geographic (STATSGO) database. The total calculated monetary value for SOC storage in the contiguous U.S. was between $4.64T (i.e., $4.64 trillion U.S. dollars, where T = trillion = 10^{12}) and $23.1T, with a midpoint value of $12.7T. Soil orders with the highest midpoint SOC storage values were 1): Mollisols ($4.21T), 2) Histosols ($2.31T), and 3) Alfisols ($1.48T). The midpoint values of SOC normalized by area within soil order boundaries were ranked: 1) Histosols ($21.58 m^{-2}), 2) Vertisols ($2.26 m^{-2}), and 3) Mollisols ($2.08 m^{-2}). The soil depth interval with the highest midpoint values of SOC storage and content was 20–100 cm ($6.18T and $0.84 m^{-2}, respectively), while the depth interval 100–200 cm had the lowest midpoint values of SOC storage ($2.88T) and content ($0.39 m^{-2}). The depth trends exemplify the prominence of SOC in the upper portions of soil. The LRRs with the highest midpoint SOC storage values were: 1) M – Central Feed Grains and Livestock Region ($1.8T), 2) T – Atlantic and Gulf Coast Lowland Forest and Crop Region ($1.26T), and 3) K – Northern Lake States Forest and Forage Region ($1.16T). The midpoint values of SOC normalized by area within LRR boundaries were ranked: 1) U – Florida Subtropical Fruit, Truck Crop, and Range Region ($6.10 m^{-2}), 2) T – Atlantic and Gulf Coast Lowland Forest and Crop Region ($5.44 m^{-2}), and 3) K – Northern Lake States Forest and Forage Region ($3.88 m^{-2}). States with the highest midpoint values of SOC storage were: 1) Texas ($1.08T), 2) Minnesota ($834B) (i.e., $834 billion U.S. dollars, where B = billion = 10^9), and 3) Florida ($742B). Midpoint values of SOC normalized by area within state boundaries were ranked: 1) Florida ($5.44 m^{-2}), 2) Delaware ($4.10 m^{-2}), and 3) Minnesota ($3.99 m^{-2}). Regions with the highest midpoint values of SOC storage were: 1) Midwest ($3.17T), 2) Southeast ($2.44T), and 3) Northern Plains ($2.35T). Midpoint values of SOC normalized by area within region boundaries were ranked: 1) Midwest ($2.73 m^{-2}), 2) Southeast ($2.31 m^{-2}), and 3) East ($1.82 m^{-2}). The reported values and trends demonstrate the need for policies with regards to SOC management, which requires incentives within administrative boundaries but informed by the geographic distribution of SOC.

Keywords: carbon emissions; CO_2; social cost; soil organic carbon (SOC)

1. Introduction

Economic valuation of soil organic carbon (SOC) is important for achieving the United Nations (UN) Sustainable Development Goals (SDGs) especially SDG 13: "Take urgent action to combat climate change and its impacts" [1]. The ecosystem services (ES) framework is often used in connection with UN SDGs because it is focused on the economic valuation of benefits people obtain from nature [2]. The ES framework includes four general categories of services: provisioning, regulating, cultural, and supporting services [2]. Soil organic carbon is included in the list of soil properties important for ecosystem services [3]. Soil organic carbon is derived from living matter and tends to be concentrated in the topsoil (Table 1). In a well-aerated soil, all of the organic compounds found in plant residue are subject to enzymatic oxidation, and this reaction is accompanied by oxygen consumption and CO_2 release [4].

Soil organic carbon is a fraction of soil organic matter (SOM) (Table 1). Soil databases provide SOM (%) and/or SOC (%) in their reports listed in the tables of soil physical properties. Soil organic matter contributes to numerous soil functions (e.g., nutrient and energy reserve, etc.), which are linked to ecosystem goods and services (e.g., nutrient storage and availability, etc.) [5]. The role of SOM in delivering these ecosystem goods and services varies with scales from local (e.g., fertility maintenance) to global (e.g., mitigation of carbon emissions) [5].

Table 1. Soil organic matter (SOM), soil organic carbon (SOC), and carbon sequestration pathways.

Soil Organic Matter (SOM)	Soil Organic Carbon (SOC)
- Fresh residue, decomposing organic matter, stable organic matter (humus), and living organisms. or - "Continuum of organic material in all stages of transformation and decomposition or stabilization [6]."	- Carbon fraction of soil organic matter.
Conversion (using Van Bemmelen factor of 0.58 or 1.724): SOM (%) = SOC (%) × 1.724 or SOC (%) = SOM (%) × 0.58 [7]	
Pathways to increased soil carbon sequestration: Additions of organic matter (e.g., compost additions, etc.); land/agricultural management (e.g., no-till operations, land conservation, etc.); afforestation, etc.	

Mitigation of carbon emissions requires human societies to examine the natural and human-derived stocks and flows of SOC in the biosphere-pedosphere-atmosphere exchange system using a combined social-ecological system-based analysis [8] (Table 2). A set of connected processes ("flows") and quantities of resources ("stocks") form a "system" [8]. Soil organic matter stocks are quantifiable amounts defined in a spatial context (e.g., kg m^{-2}) [8]. Flows into or from these stocks are fluxes (e.g., the concentration of carbon dioxide (CO_2) sequestered or released in parts per million per meter squared per year) [8]. There is an on-going effort to provide an economic value for SOC, which can be a challenging task because SOC provides a wide range of ecosystem goods and services. Economic valuation of carbon sequestration or release via CO_2 is of particular interest because it involves the atmosphere, which is a common-pool resource (Table 2) [9]. Carbon sequestration or release via CO_2 is a complex process in the biosphere-pedosphere-atmosphere exchange system, which involves various types of ownership, market information, and degree of market information availability (Table 2) [9]. Mixed ownership (e.g., government, private, etc.) commoditized organic matter from the biosphere and soil organic matter from the pedosphere in the market, but CO_2 emissions to the atmosphere (a common-pool resource) resulting from soil disturbance (e.g., cultivation) have unidentified market value, which creates "non-capturable" outcomes (externalities) for a society [9]. According to Groshans et al., 2019 [9], the unidentified market value of SOC based on the avoided social cost of carbon emissions "can either have a positive effect (a socially optimal amount should be greater than the current amount) or a negative effect (the socially optimal amount should be less than the current amount) on the costs of climate control after a price of SOC is identified."

Table 2. Biosphere–pedosphere–atmosphere ecosystem services exchange, stocks, goods, flows (represented by arrows), and ownership in relation to soil organic matter (SOM) and soil organic carbon (SOC) (adapted from Groshans et al., 2019 [9]).

Biosphere	**Pedosphere**	**Atmosphere**
Organic matter stock (OM)	Soil-based stock (SOM, SOC)	Atmospheric stock (e.g., CO_2)
Biotic	Biotic	Abiotic-Biotic
	Ownership	
Mixed (e.g., government, private, etc.)	Mixed (e.g., government, private, etc.)	Common-pool resource
	Market information	
Partially identified market value (e.g., market value of compost, etc.)	Partially identified market value (e.g., avoided social cost of carbon emissions, etc.)	Unidentified market value Positive effect (socially optimal amount should be greater than the current amount) Negative effect (socially optimal amount should be less that the current amount)
	Market information availability	
Partial market information	Partial market information	Little or no market information

Although the CO_2 emissions are considered "non-capturable" outcomes (externalities) if they are already emitted into the atmosphere, this study proposes to monetize the potential CO_2 emissions from soils based on SOC values reported in soil survey databases. This information could also be determined for more detailed spatial scales through direct and remotely acquired carbon data as needed. One useful approach for estimating an economic value for SOC is based on the social cost of carbon (SC-CO_2) and avoided emissions associated with sequestration of organic carbon in soils [9]. The U.S. Environmental Protection Agency (EPA) has derived a value of $42 per metric ton of CO_2 for the SC-CO_2 in the U.S., which is applicable for the year 2020 based on 2007 U.S. dollars and an average discount rate of 3% [10]. Although this assigned value for the SC-CO_2 is intended to be a comprehensive estimate of climate change damages, it is likely an underestimate of the true damages and cost of CO_2 emissions [9,10].

The objective of this study was to assess the value of SOC in the contiguous U.S. using the social cost of carbon (SC-CO_2) and avoided emissions provided by carbon sequestration. This study provides the monetary values of SOC by soil depth (0–20, 20–100, 100–200 cm) across the contiguous U.S. and by considering different spatial aggregation levels (i.e., state, region, land resource region (LRR)) using information previously reported by Guo et al. (2006) [11], who estimated the inventory of SOC for the conterminous U.S. using the State Soil Geographic (STATSGO).

2. Materials and Methods

2.1. The Accounting Framework

This study used both biophysical (science-based) and administrative (boundary-based) accounts to calculate monetary values for SOC (Table 3).

Table 3. A conceptual overview of the accounting framework used in this study (adapted from Groshans et al., 2018 [12]).

Biophysical Accounts (Science-Based)	Administrative Accounts (Boundary-Based)	Monetary Account(s)	Benefit(s)	Total Value
Soil extent:	Administrative extent:	Ecosystem good(s) and service(s):	Sector:	Types of value:
Separate constituent stock: Soil organic carbon (SOC)				
			Environment:	Social cost of carbon ($SC\text{-}CO_2$) and avoided emissions:
- Soil order - Soil depth	- Country - State - Region - Land Resource Region (LRR)	- Regulating (e.g., carbon sequestration)	- Carbon sequestration in soil organic matter (SOM)	- $42 per metric ton of CO_2 (2007 U.S. dollars with an average discount rate of 3% [10])

2.2. Monetary Valuation Approach

For the contiguous U.S., the estimated values for the minimum, midpoint, and maximum total SOC storage (in Mg or metric tons) and content (in kg m^{-2}) for all soils by depth (0–20, 20–100, 100–200 cm), state, region, and land resource region (LRR) were obtained from Guo et al. [11]. Soil organic carbon storage and content numbers were then converted to U.S. dollars and dollars per square meter in Microsoft Excel using the following equations, with a social cost of carbon of \$42/Mg CO_2:

$$\$ = (\text{SOC Storage, Mg}) \times \frac{44\ \text{Mg CO}_2}{12\ \text{Mg SOC}} \times \frac{\$42}{\text{Mg CO}_2} \quad (1)$$

$$\frac{\$}{\text{m}^2} = \left(\text{SOC Content, } \frac{\text{Mg}}{\text{m}^2}\right) \times \frac{1\ \text{Mg}}{10^3\ \text{kg}} \times \frac{44\ \text{Mg CO}_2}{12\ \text{Mg SOC}} \times \frac{\$42}{\text{Mg CO}_2} \quad (2)$$

For example, for the State of Iowa, Guo et al. (2006) [11] reported midpoint SOC storage and content numbers of 2944×10^6 Mg and 20.5 kg·m^{-2}, respectively. Using these two numbers together with a conversion factor for SOC to CO_2 and the EPA dollar value for the $SC\text{-}CO_2$ results in a total SOC value of \$$4.53 \times 10^{11}$ (about \$0.45T or 0.45 trillion U.S. dollars) and an area-normalized SOC value of \$3.16 m^{-2}, respectively.

3. Results

Soil organic carbon (SOC) in the contiguous U.S., that either formed naturally (e.g., decomposition of plant and animal remnants etc.) or anthropogenically (e.g., compost additions etc.) in the soil can be monetarily valued based on the avoided social cost of carbon ($SC\text{-}CO_2$) from the long-term damage as a result of the emission of a metric ton of carbon dioxide (CO_2). The estimated values (minimum, mid-value, and maximum) associated with SOC in the contiguous U.S. vary by soil order, depth, land resource regions (LRR), state, and region. The total SOC storage value in the contiguous U.S. is between \$4.64T (i.e., \$4.64 trillion U.S. dollars, where T = trillion = 10^{12}) and \$23.1T, with a midpoint value of \$12.7T. Normalized by area across the entire contiguous U.S., the SOC content value is between \$0.63 m^{-2} and \$3.14 m^{-2}, with a midpoint value of \$1.72 m^{-2}.

3.1. Value of SOC by Soil Order

The soil orders with the highest total SOC storage value were: 1) Mollisols ($4.21T), 2) Histosols ($2.31T), and 3) Alfisols ($1.48T) (Table 4). The value of SOC based on area density within soil order boundaries were ranked: 1) Histosols ($21.58 m^{-2}), 2) Vertisols ($2.26 m^{-2}), and 3) Mollisols ($2.08 m^{-2}). The soil orders with the highest values of SOC storage and area-density were found to be either slightly (e.g., Histosols, etc.) or intermediately weathered soils (e.g., Mollisols, etc.) (Table 4).

Table 4. Total and area-normalized values of soil organic carbon (SOC) storage in the upper 2 m within the contiguous United States (U.S.), based on SOC numbers from Guo et al., 2006 [11] and a social cost of carbon (SC-CO_2) of $42 per metric ton of CO_2.

Soil Order	Total Area (km^2)	Total Value			Value per Area		
		Min. ($)	**Mid. ($)**	**Max. ($)**	**Min. ($ m^{-2})**	**Mid. ($ m^{-2})**	**Max. ($ m^{-2})**
Slight weathering							
Entisols	1,054,015	2.97×10^{11}	1.30×10^{12}	2.56×10^{12}	0.28	1.23	2.43
Inceptisols	787,254	3.08×10^{11}	1.08×10^{12}	2.11×10^{12}	0.43	1.37	2.68
Histosols	107,249	1.06×10^{12}	2.31×10^{12}	4.03×10^{12}	9.84	21.58	37.56
Gelisols	-	-	-	-	-	-	-
Andisols	68,666	5.04×10^{10}	1.13×10^{11}	1.98×10^{11}	0.74	1.65	2.88
Intermediate weathering							
Aridisols	809,423	1.45×10^{11}	5.02×10^{11}	9.52×10^{11}	0.18	0.62	1.17
Vertisols	132,433	1.10×10^{11}	2.99×10^{11}	5.19×10^{11}	0.83	2.26	3.93
Alfisols	1,274,102	4.56×10^{11}	1.48×10^{12}	2.77×10^{12}	0.35	1.16	2.17
Mollisols	2,020,694	1.82×10^{12}	4.21×10^{12}	7.10×10^{12}	0.91	2.08	3.51
Strong weathering							
Spodosols	250,133	1.11×10^{11}	4.73×10^{11}	9.82×10^{11}	0.45	1.89	3.93
Ultisols	860,170	2.52×10^{11}	9.43×10^{11}	1.84×10^{12}	0.29	1.09	2.14
Oxisols	-	-	-	-	-	-	-
Totals	**7,364,139**	**4.64×10^{12}**	**1.27×10^{13}**	**2.31×10^{13}**			

Note: Total areas, and thus, the subsequent calculated values, for Oxisols and Gelisols, were negligible and, therefore, are not shown. Min. = minimum; Mid. = midpoint; Max. = maximum.

3.2. Value of SOC by Soil Depth in the Contiguous U.S.

The depth with the highest mid-point value of SOC storage was the interval 20–100 cm ($6.18T), while the depth with the highest mid-point value of SOC area-density was in the same interval 20–100 cm ($0.84 m^{-2}) (Table 5). The interval 100–200 cm had the lowest mid-point SOC storage ($2.88T) and lowest area-density ($0.39 m^{-2}) mid-point value.

Table 5. Total and area-normalized values of soil organic carbon (SOC) by depth for the contiguous United States (U.S.), based on SOC numbers from Guo et al., 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

Depth (cm)	Total Value			Value per Area		
	Min. ($)	**Mid. ($)**	**Max. ($)**	**Min. ($ m^{-2})**	**Mid. ($ m^{-2})**	**Max. ($ m^{-2})**
0–20	1.79×10^{12}	3.67×10^{12}	6.04×10^{12}	0.24	0.50	0.82
20–100	2.13×10^{12}	6.18×10^{12}	1.14×10^{13}	0.29	0.84	1.54
100–200	7.39×10^{11}	2.88×10^{12}	5.67×10^{12}	0.10	0.39	0.77
Totals	**4.65×10^{12}**	**1.27×10^{13}**	**2.31×10^{13}**			

Note: Min. = minimum; Mid. = midpoint; Max. = maximum.

3.3. Value of SOC by Land Resource Regions (LRRs) in the Contiguous U.S.

Land Resource Regions (LRRs) are defined by the U.S. Department of Agriculture (USDA) using major land resource area (MLRA) and agricultural markets, which are denoted using capital letters (e.g., A, B, C, etc.; see Table 6 notes). The contiguous U.S. (with the exception of Alaska and Hawaii) comprises 20 of the 28 LRRs. The LRRs with the highest total SOC storage value were: 1) M—Central Feed Grains and Livestock Region ($1.8T), 2) T—Atlantic and Gulf Coast Lowland Forest and Crop Region ($1.26T), and 3) K—Northern Lake States Forest and Forage Region ($1.16T) (Figure 1). The value of SOC based on area density within LRR boundaries were ranked: 1) U—Florida Subtropical Fruit, Truck Crop and Range Region ($6.10 m^{-2}), 2) T—Atlantic and Gulf Coast Lowland Forest and Crop Region ($5.44 m^{-2}), and 3) K—Northern Lake States Forest and Forage Region ($3.88 m^{-2}).

Table 6. Total and area-normalized soil organic carbon (SOC) values by Land Resource Regions (LRRs) for the contiguous U.S., based on SOC numbers from Guo et al. 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

LRRs	Area (km^2)	Total Value			Value per Area		
		Min. ($)	Mid. ($)	Max. ($)	Min. ($ m^{-2})	Mid. ($ m^{-2})	Max. ($ m^{-2})
A	181,215	1.63×10^{11}	3.97×10^{11}	7.06×10^{11}	0.89	2.19	3.90
B	259,284	1.33×10^{11}	3.13×10^{11}	5.49×10^{11}	0.51	1.20	2.11
C	146,884	8.16×10^{10}	2.27×10^{11}	3.89×10^{11}	0.55	1.56	2.65
D	1,268,922	2.42×10^{11}	8.69×10^{11}	1.67×10^{12}	0.18	0.68	1.31
E	521,994	2.25×10^{11}	6.34×10^{11}	1.20×10^{12}	0.43	1.22	2.29
F	351,842	2.53×10^{11}	7.40×10^{11}	1.35×10^{12}	0.72	2.11	3.83
G	521,442	1.65×10^{11}	4.84×10^{11}	8.59×10^{11}	0.32	0.92	1.65
H	583,820	3.57×10^{11}	9.92×10^{11}	1.73×10^{12}	0.62	1.69	2.96
I	169,689	9.49×10^{10}	2.61×10^{11}	4.82×10^{11}	0.55	1.54	2.83
J	139,624	9.78×10^{10}	2.54×10^{11}	4.42×10^{11}	0.69	1.82	3.16
K	300,269	4.83×10^{11}	1.16×10^{12}	2.09×10^{12}	1.60	3.88	6.95
L	119,997	1.72×10^{11}	3.85×10^{11}	6.57×10^{11}	1.43	3.22	5.48
M	717,615	9.29×10^{11}	1.80×10^{12}	2.82×10^{12}	1.29	2.51	3.93
N	603,434	1.44×10^{11}	5.54×10^{11}	1.14×10^{12}	0.23	0.92	1.89
O	94,652	4.14×10^{10}	1.58×10^{11}	3.14×10^{11}	0.43	1.68	3.31
P	677,160	2.62×10^{11}	9.51×10^{11}	1.78×10^{12}	0.39	1.40	2.63
R	300,536	1.77×10^{11}	6.44×10^{11}	1.35×10^{12}	0.59	2.14	4.48
S	99,147	3.34×10^{10}	1.14×10^{11}	2.38×10^{11}	0.34	1.16	2.40
T	231,303	4.12×10^{11}	1.26×10^{12}	2.39×10^{12}	1.79	5.44	10.32
U	85,410	1.79×10^{11}	5.21×10^{11}	9.48×10^{11}	2.09	6.10	11.10
Totals	**7,374,239**	$\mathbf{4.65 \times 10^{12}}$	$\mathbf{1.27 \times 10^{13}}$	$\mathbf{2.31 \times 10^{13}}$			

Note: A = Northwestern Forest, Forage, and Specialty Crop Region; B = Northwestern Wheat and Range Region; C = California Subtropical Fruit, Truck, and Specialty Crop Region; D = Western Range and Irrigated Region; E = Rocky Mountain Range and Forest Region; F = Northern Great Plains Spring Wheat Region; G = Western Great Plains Range and Irrigated Region; H = Central Great Plains Winter Wheat and Range Region; I = Southwest Plateaus and Plains Range and Cotton Region; J = Southwestern Prairies Cotton and Forage Region; K = Northern Lake States Forest and Forage Region; L = Lake States Fruit, Truck, and Dairy Region; M = Central Feed Grains and Livestock Region; N = East and Central Farming and Forest Region; O = Mississippi Delta Cotton and Feed Grains Region; P = South Atlantic and Gulf Slope Cash Crops, Forest and Livestock Region; R = Northeastern Forage and Forest Region; S = Northern Atlantic Slope Diversified Farming Region; T = Atlantic and Gulf Cost Lowland Forest and Crop Region; U = Florida Subtropical Fruit, Truck Crop, and Range Region; Min. = minimum; Mid. = midpoint; Max. = maximum.

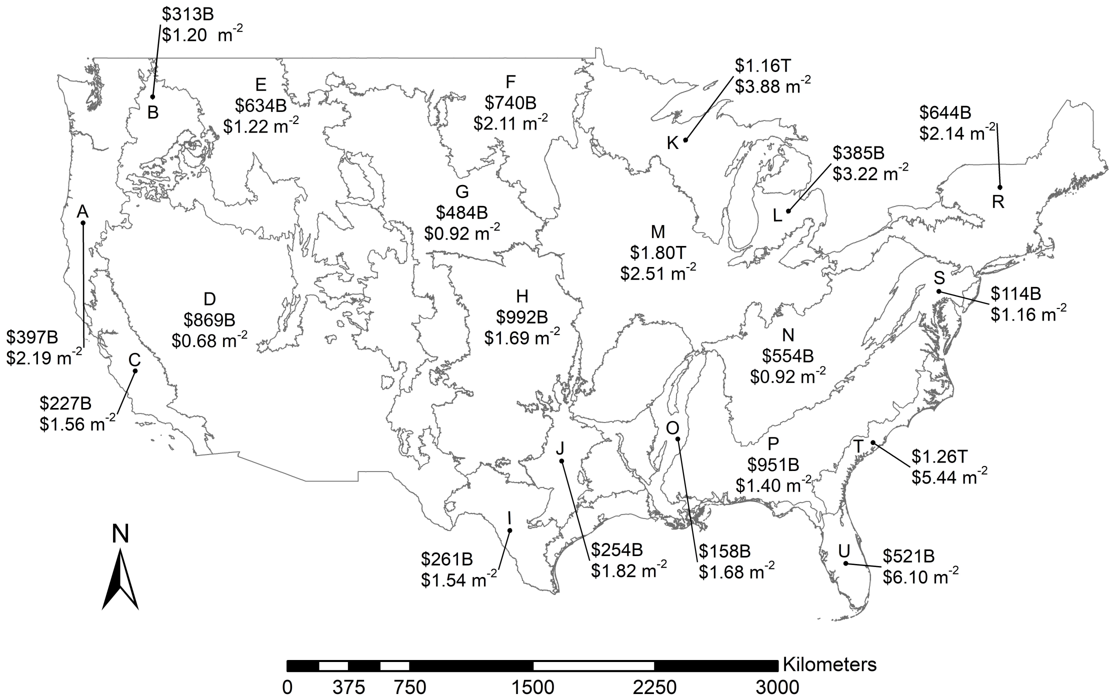

Figure 1. The total (midpoint) value (top number) and (midpoint) value normalized by area (bottom number) of soil organic carbon (SOC) for different Land Resources Regions (LRRs) in the contiguous United States (U.S.), based on SOC numbers from Guo et al. 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

3.4. Value of SOC by States and Regions in the Contiguous U.S.

States with the highest total SOC storage value were: (1) Texas ($1.08T), (2) Minnesota ($834B), and (3) Florida ($742B) (Figure 2, Table 7). The value of SOC based on area density within state boundaries were ranked: (1) Florida ($5.44 m^{-2}), (2) Delaware ($4.10 m^{-2}), and (3) Minnesota ($3.99 m^{-2}) (Table 7, Figure 2). The regions with the highest total SOC storage value were: (1) Midwest ($3.17T), (2) Southeast ($2.44T), and (3) Northern Plains ($2.35T) (Table 7, Figure 3). The value of SOC based on area density within regions boundaries were ranked: (1) Midwest ($2.73 m^{-2}), (2) Southeast ($2.31 m^{-2}), and (3) East ($1.82 m^{-2}) (Table 7, Figure 2).

4. Discussion

Sustainable SOC management is an important economic issue because SOC is critical for food production, but it also provides a regulating service, which can be valued based on the avoided social cost of carbon emissions. Much of the original levels of SOC has been lost to the atmosphere through the original conversion of "native" grasslands and forests to agricultural land, which globally has caused a loss of SOC between 20–60% [12–14]. North American farmland has lost about half of its original content of SOM [15]. Our study is based on more recent soil inventories, which represent the SOC status after this original loss. We have estimated a monetary value for SOC, based on SC-CO_2 and the avoided emissions/damages that are gained by sequestration of CO_2 from the atmosphere in the contiguous U.S. by soil order, soil depth, land resource region (LRR), state, and region using information from the State Soil Geographic (STATSGO) database. Climate, soil type, and geographic location impact the SOC values for the SC-CO_2 (Figure 4). The SOC values for the SC-CO_2 are decreasing with the increase in temperature and dryness (Figure 4).

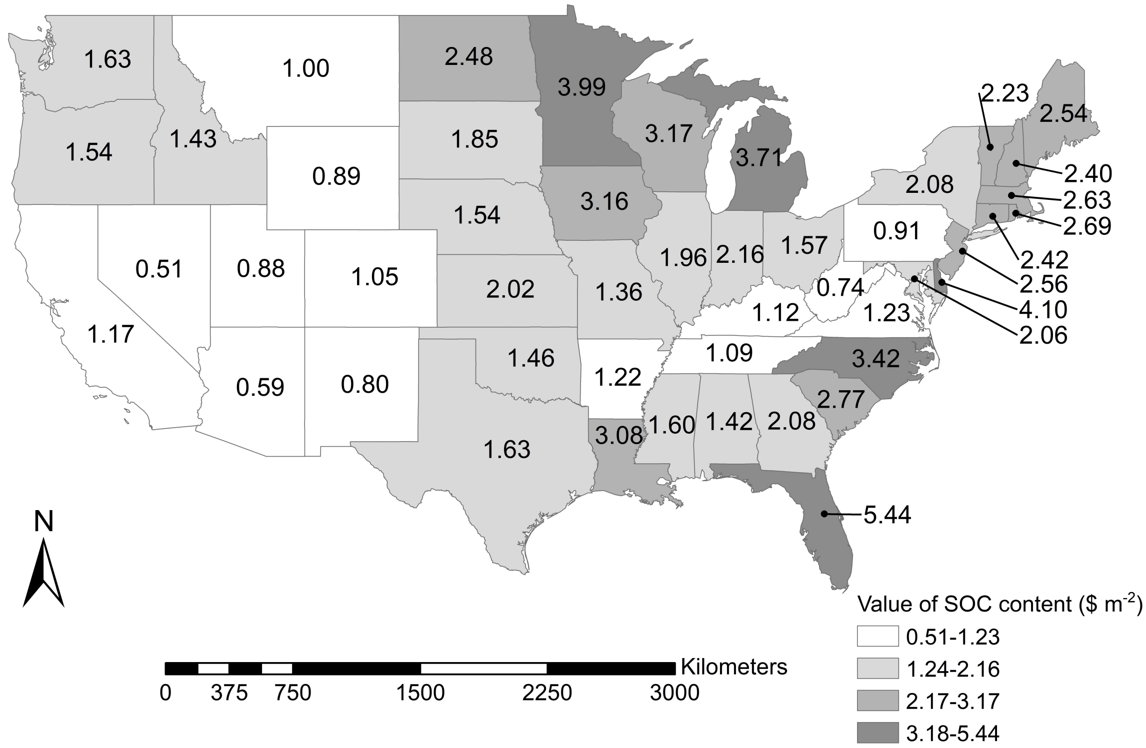

Figure 2. Midpoint values of soil organic carbon (SOC) normalized by land area ($ m^{-2}) for states in the contiguous United States (U.S.), based on SOC numbers from Guo et al. 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

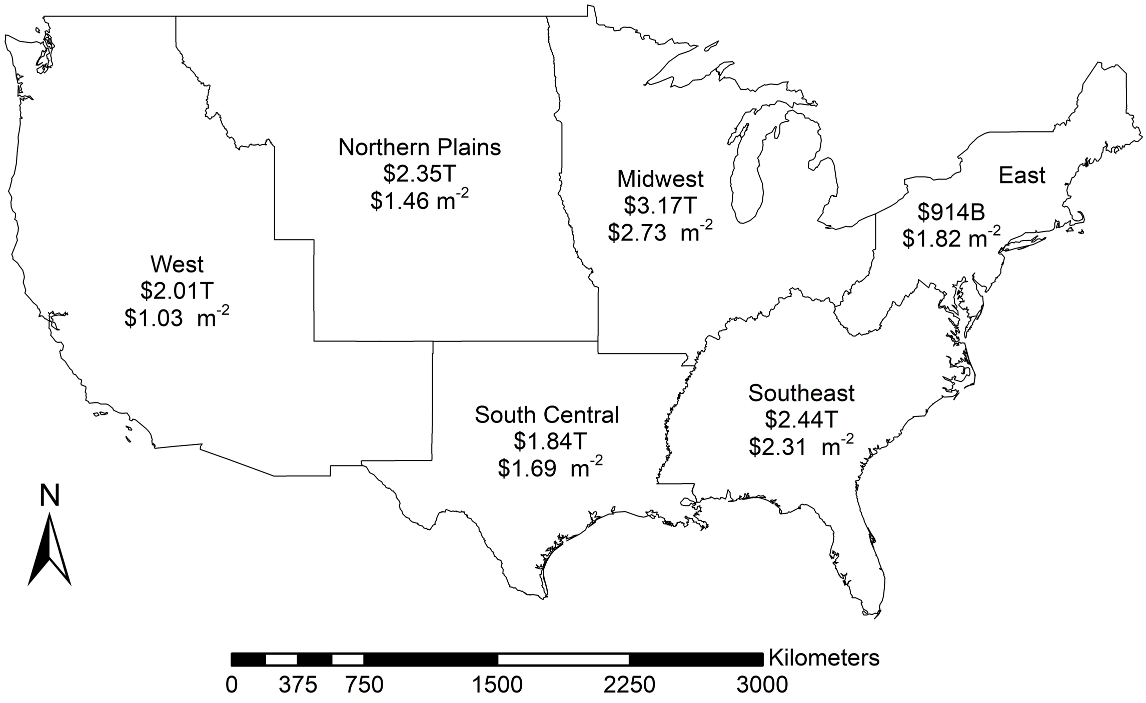

Figure 3. Total (midpoint) soil organic carbon (SOC) values (top number), and midpoint SOC values normalized by land area (bottom number), for different regions in the contiguous United States (U.S.), based on SOC numbers from Guo et al. 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

Table 7. Total and area-normalized soil organic carbon (SOC) values by state and region for the contiguous United States (U.S.), based on soil organic carbon (SOC) numbers from Guo et al. 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

State (Region)	Area (km^2)	Total Value			Value per Area		
		Min. ($)	Mid. ($)	Max. ($)	Min. ($ m^{-2})	Mid. ($ m^{-2})	Max. ($ m^{-2})
Connecticut	12,406	7.70×10^{9}	3.00×10^{10}	6.51×10^{10}	0.63	2.42	5.25
Delaware	5043	4.31×10^{9}	2.06×10^{10}	4.47×10^{10}	0.86	4.10	8.86
Massachusetts	18,918	1.16×10^{10}	4.99×10^{10}	1.07×10^{11}	0.62	2.63	5.67
Maryland	25,266	1.28×10^{10}	5.21×10^{10}	1.11×10^{11}	0.51	2.06	4.42
Maine	80,584	6.50×10^{10}	2.05×10^{11}	4.12×10^{11}	0.80	2.54	5.11
New Hampshire	22,801	1.05×10^{10}	5.50×10^{10}	1.24×10^{11}	0.46	2.40	5.45
New Jersey	17,788	1.62×10^{10}	4.54×10^{10}	9.06×10^{10}	0.91	2.56	5.08
New York	118,432	7.39×10^{10}	2.46×10^{11}	4.98×10^{11}	0.63	2.08	4.20
Pennsylvania	115,291	2.59×10^{10}	1.05×10^{11}	2.28×10^{11}	0.23	0.91	1.97
Rhode Island	2583	2.00×10^{9}	6.93×10^{9}	1.48×10^{10}	0.79	2.70	5.71
Vermont	23,764	1.00×10^{10}	5.30×10^{10}	1.19×10^{11}	0.42	2.23	5.02
West Virginia	61,448	1.00×10^{10}	4.56×10^{10}	9.86×10^{10}	0.17	0.74	1.60
(East)	**504,325**	$\mathbf{2.50 \times 10^{11}}$	$\mathbf{9.14 \times 10^{11}}$	$\mathbf{1.91 \times 10^{12}}$	**0.49**	**1.82**	**3.79**
Iowa	143,801	2.95×10^{11}	4.53×10^{11}	6.29×10^{11}	2.05	3.16	4.37
Illinois	143,948	1.41×10^{11}	2.82×10^{11}	4.45×10^{11}	0.97	1.96	3.10
Indiana	93,584	8.22×10^{10}	2.02×10^{11}	3.50×10^{11}	0.88	2.16	3.74
Michigan	147,532	2.55×10^{11}	5.48×10^{11}	9.21×10^{11}	1.72	3.71	6.24
Minnesota	209,223	3.57×10^{11}	8.34×10^{11}	1.47×10^{12}	1.71	3.99	7.01
Missouri	177,484	1.02×10^{11}	2.40×10^{11}	4.15×10^{11}	0.57	1.36	2.34
Ohio	105,442	5.22×10^{10}	1.65×10^{11}	3.12×10^{11}	0.49	1.57	2.96
Wisconsin	140,542	1.93×10^{11}	4.45×10^{11}	7.82×10^{11}	1.37	3.17	5.56
(Midwest)	**1,161,556**	$\mathbf{1.48 \times 10^{12}}$	$\mathbf{3.17 \times 10^{12}}$	$\mathbf{5.32 \times 10^{12}}$	**1.28**	**2.73**	**4.57**
Arkansas	135,832	5.19×10^{10}	1.66×10^{11}	3.13×10^{11}	0.39	1.22	2.31
Louisiana	109,273	6.87×10^{10}	3.36×10^{11}	7.34×10^{11}	0.63	3.08	6.71
Oklahoma	176,647	8.92×10^{10}	2.58×10^{11}	4.63×10^{11}	0.51	1.46	2.62
Texas	660,649	3.92×10^{11}	1.08×10^{12}	1.93×10^{12}	0.60	1.63	2.91
(South Central)	**1,082,402**	$\mathbf{6.01 \times 10^{11}}$	$\mathbf{1.48 \times 10^{12}}$	$\mathbf{3.44 \times 10^{12}}$	**0.55**	**1.69**	**3.17**
Alabama	130,948	5.17×10^{10}	1.86×10^{11}	3.56×10^{11}	0.40	1.42	2.73
Florida	136,490	2.60×10^{11}	7.42×10^{11}	1.35×10^{12}	1.91	5.44	9.86
Georgia	149,285	1.01×10^{11}	3.10×10^{11}	5.67×10^{11}	0.68	2.08	3.80
Kentucky	101,847	2.99×10^{10}	1.14×10^{11}	2.28×10^{11}	0.29	1.12	2.25
Mississippi	122,583	4.30×10^{10}	1.97×10^{11}	3.81×10^{11}	0.35	1.60	3.11
North Carolina	125,522	1.61×10^{11}	4.30×10^{11}	7.77×10^{11}	1.28	3.42	6.19
South Carolina	78,489	6.36×10^{10}	2.17×10^{11}	4.06×10^{11}	0.82	2.77	5.17
Tennessee	104,277	2.59×10^{10}	1.14×10^{11}	2.29×10^{11}	0.25	1.09	2.19
Virginia	102,714	3.33×10^{10}	1.27×10^{11}	2.50×10^{11}	0.32	1.23	2.43
(Southeast)	**1,052,154**	$\mathbf{7.69 \times 10^{11}}$	$\mathbf{2.44 \times 10^{12}}$	$\mathbf{4.54 \times 10^{12}}$	**0.72**	**2.31**	**4.31**
Colorado	253,888	9.72×10^{10}	2.68×10^{11}	4.83×10^{11}	0.39	1.05	1.91
Kansas	212,325	1.72×10^{11}	4.28×10^{11}	7.17×10^{11}	0.82	2.02	3.37
Montana	350,837	1.35×10^{11}	3.52×10^{11}	6.42×10^{11}	0.39	1.00	1.83
North Dakota	178,589	1.42×10^{11}	4.42×10^{11}	8.19×10^{11}	0.80	2.48	4.59
Nebraska	198,419	1.23×10^{11}	3.06×10^{11}	5.11×10^{11}	0.62	1.54	2.57
South Dakota	191,914	1.27×10^{11}	3.53×10^{11}	6.23×10^{11}	0.66	1.85	3.25
Wyoming	229,275	5.99×10^{10}	2.06×10^{11}	3.87×10^{11}	0.26	0.89	1.69
(Northern Plains)	**1,615,247**	$\mathbf{8.56 \times 10^{11}}$	$\mathbf{2.35 \times 10^{12}}$	$\mathbf{4.18 \times 10^{12}}$	**0.52**	**1.46**	**2.59**
Arizona	266,867	3.36×10^{10}	1.54×10^{11}	3.05×10^{11}	0.12	0.59	1.14
California	353,973	1.37×10^{11}	4.13×10^{11}	7.46×10^{11}	0.39	1.17	2.11
Idaho	197,155	1.02×10^{11}	2.83×10^{11}	5.28×10^{11}	0.51	1.43	2.68
New Mexico	284,358	5.21×10^{10}	2.30×10^{11}	4.46×10^{11}	0.18	0.80	1.57
Nevada	269,415	3.74×10^{10}	1.37×10^{11}	2.72×10^{11}	0.14	0.51	1.00
Oregon	239,876	1.56×10^{11}	3.68×10^{11}	6.46×10^{11}	0.65	1.54	2.70
Utah	185,030	6.13×10^{10}	1.61×10^{11}	2.88×10^{11}	0.34	0.88	1.56
Washington	161,881	1.12×10^{11}	2.63×10^{11}	4.64×10^{11}	0.69	1.63	2.86
(West)	**1,958,556**	$\mathbf{6.92 \times 10^{11}}$	$\mathbf{2.01 \times 10^{12}}$	$\mathbf{3.70 \times 10^{12}}$	**0.35**	**1.03**	**1.89**
Totals	**7,374,238**	$\mathbf{4.64 \times 10^{12}}$	$\mathbf{1.27 \times 10^{13}}$	$\mathbf{2.31 \times 10^{13}}$			

Note: Min. = minimum; Mid. = midpoint; Max. = maximum.

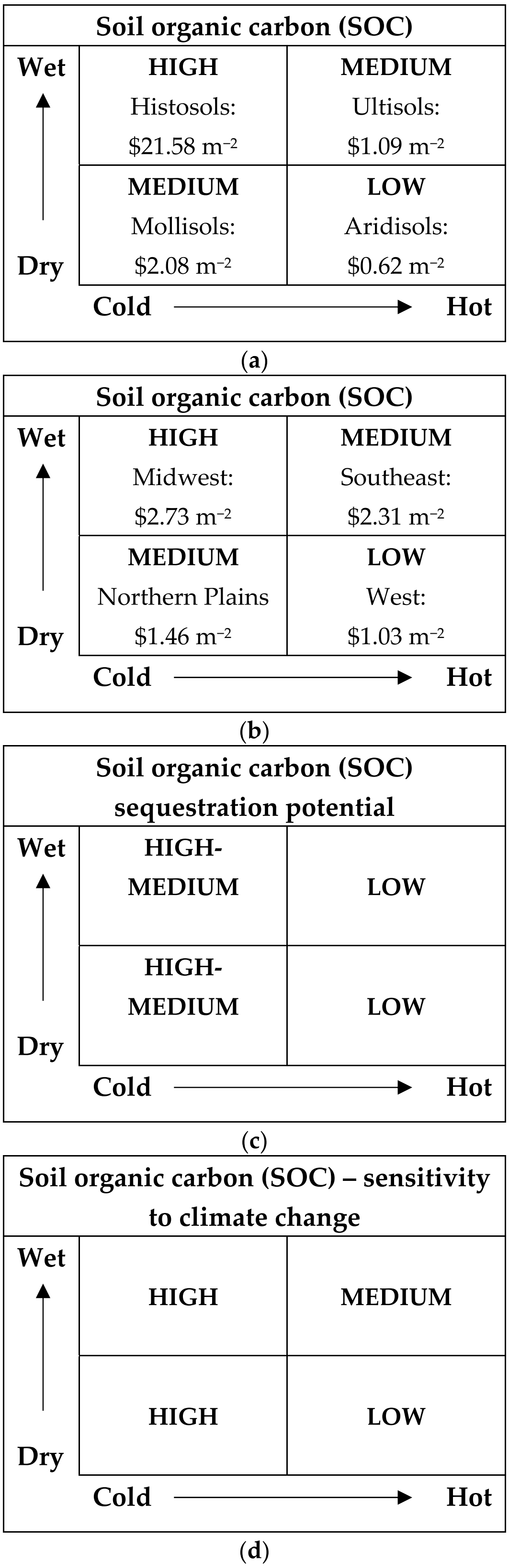

Figure 4. Climate effect on the value of soil organic carbon (SOC) stocks in the soils based on the avoided SC-CO_2 of $42 per metric ton of CO_2, and SOC sequestration potential: (**a**) biophysical units (e.g., soil orders), (**b**) administrative units (e.g., regions), (**c**) SOC sequestration potential, and (**d**) SOC sensitivity to climate change.

Soil organic carbon values for the SC-CO_2 vary by soil type with Histosols having the highest value and Aridisols having the lowest value, which can be explained by the climate and geographic variation (Figure 4). Consequently, this variation impacts the SC-CO_2 values at the administrative levels (e.g., region) with the West (dominated by soil order of Aridisols) having the lowest values. Midwest regions have the highest SC-CO_2 values because they are dominated by Mollisols and presence of Histosols, which have the highest SC-CO_2 values. This biogeophysical variation limits the maximum feasible SOC sequestration potential, which is further impacted by human soil management decisions, and climate change [16]. Because this study is based on numbers reported by Guo et al., 2006 [11], which cover only the 48 lower states (and not Alaska), Gelisols were negligible. However, climate change scientists are particularly worried about the thawing of permafrost soils in Northern climates because of the very large releases of CO_2 that will result. Hence, in Figure 5, it will be equivalent to taking a "cold" soil and warming it up to being a "hot" soil. According to Table 8, increasing global temperatures will lead to increases in all soil respiration rates and decreases in turnover times. Larger changes will likely be observed for soils/vegetation types that are colder and wetter, while smaller changes will likely occur for soils/vegetation types that are now warmer and dryer. Peatlands and permafrost are particularly sensitive to climate change [17] and predicted to have a potential loss of belowground C stocks by 100 Pg each by 2100 due to global warming [18]. Soil organic matter levels can be managed using sustainable soil management (e.g., no-till, etc.), but increasing SOM sequestration in soils will be controlled by numerous factors (Table 9).

Table 8. Soil respiration values in various ecosystems (adapted from Raich and Schlesinger, 1992 [19]), based on soil organic carbon (SOC) numbers from Guo et al., 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2.

Ecosystem (Vegetation Type)	Mean Soil Profile C (Mg ha^{-1})	Topsoil Turnover Time (years)	Topsoil Soil Respiration (Mg ha^{-1})	Value of Topsoil Soil Respiration ($ ha^{-1})
Swamps and marshes	723	520	2.0	84.0
Tundra	204	490	0.6	25.2
Boreal forest	206	91	3.2	134.4
Temperate grassland	189	61	4.4	184.8
Tropical lowland forest	287	38	10.9	457.8
Desert scrub	58	37	2.2	92.4
Temperate forest	134	29	6.6	277.2
Cultivated soil	79	21	5.4	226.8
Tropical grassland	42	10	6.3	264.6

Table 9. Factors controlling biosphere–pedosphere–atmosphere input-output exchange in relation to soil organic matter (SOM) and soil organic carbon (SOC) (adapted from Davidson and Janssens, 2006 [20]).

INPUT		**OUTPUT**
Biosphere ⟷	**Pedosphere** ⟷	**Atmosphere**
Organic matter stock (OM)	Soil-based stock (SOM, SOC)	Atmospheric stock (e.g., CO_2)
Factors controlling the main inputs and outputs of SOC		
• Net primary productivity • Climate • Site fertility • Hydrology • Species composition		• Temperature • Water • Oxygen • Substrate quality • Disturbance (e.g., fire, etc.) • Physical and chemical protection etc.

Increases of SOM to levels similar to the "native" state is only possible through extra additions of carbon (e.g., plant residue), but much of this carbon will be decomposed and released as CO_2 fluxes over weeks, months, and years with corresponding costs associated with SC-CO_2 emissions (Figures 5 and 6). These values of SC-CO_2 vary by C pools (e.g., labile, recalcitrant) with some forms of recalcitrant C essentially become inert [21]. According to Figure 5, the contribution of recalcitrant C may have little contribution to CO_2 flux. Getting the carbon very deep in the soil may be the only way to achieve very long-term sequestration of SOM/SOC. The carbon would need to reside in an environment that has little oxygen available to limit aerobic microbial activity/respiration. It would also help if the organic molecules were very large and complex—attributes that make microbial degradation more difficult. The positive implications of assessing the value of SOC based on the SC-CO_2 at different scales and boundaries (e.g., state, region, LRR, etc.) include allocating the appropriate amount of responsibility for externalities generated by SOC for administrative units that possess greater SOC values (Figure 7).

Plant detrital inputs		
High N, low lignin		Low N, high lignin
Belowground organic matter		
Fast ←→	Slow ←→	Passive
CO_2 flux from various C pools and its value		
410 g m^{-2} year^{-1}	4 g m^{-2} year^{-1}	5 g m^{-2} year^{-1}
$0.01722 m^{-2} year^{-1}	$0.00017 m^{-2} year^{-1}	$0.00021 m^{-2} year^{-1}
Properties of C pools		
Labile ←→		Recalcitrant
Short residence time ←→		Long residence time
Temperature-sensitive ←→		Disputed temperature sensitivity

Figure 5. Properties of soil organic carbon (SOC) pools (CENTURY model), and values of CO_2 fluxes based on the avoided SC-CO_2 of $42 per metric ton of CO_2, and SOC sequestration potential (adapted from Davidson and Janssens, 2006 [20]; Coyne and Thompson, 2006 [22]).

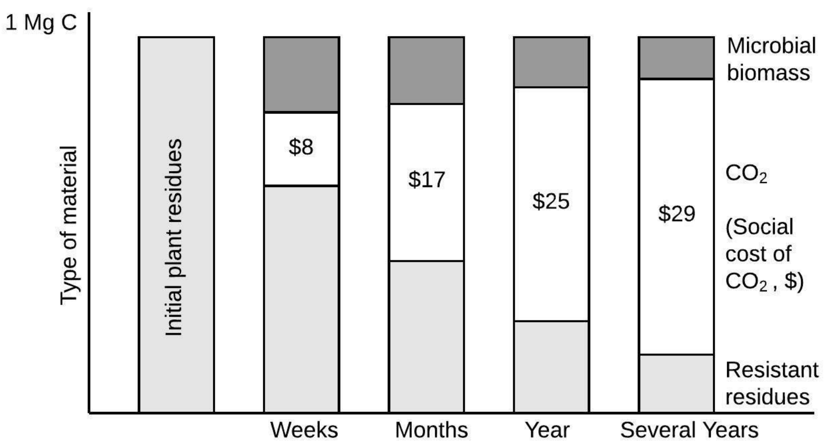

Figure 6. Physical changes during plant residue decomposition in soil, and values of CO_2 fluxes based on the avoided SC-CO_2 of $42 per metric ton of CO_2, and soil organic carbon (SOC) sequestration potential (adapted from Coyne and Thompson, 2006 [22]).

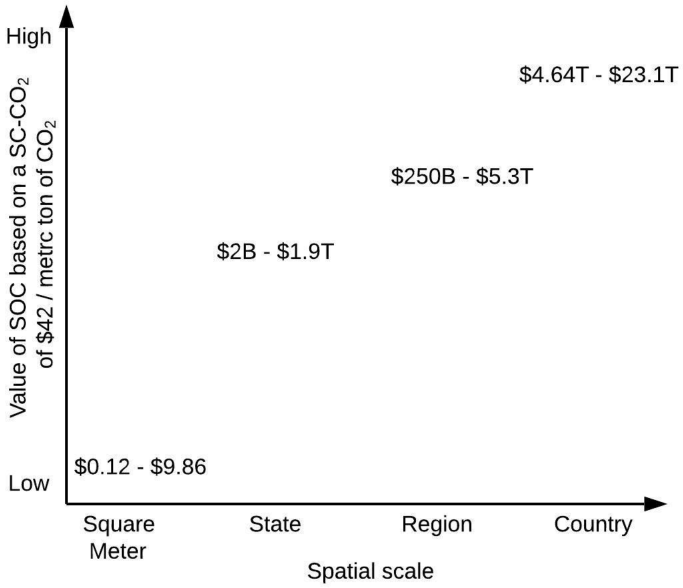

Figure 7. Scale and cost of soil organic carbon (SOC) midpoint values in the contiguous United States (U.S.), based on SOC numbers from Guo et al., 2006 [11] and a SC-CO_2 of $42 per metric ton of CO_2 (i.e., $ 2 billion U.S. dollars, where B = billion = 10^9; $1.9 trillion U.S. dollars, where T = trillion = 10^{12}).

Soil organic carbon stocks are dynamically changing based on agricultural and other uses. From a market perspective, food production (with internal value) is mostly carried out by private entities (e.g., farmers, etc.), while the benefits/costs of CO_2 sequestration or release from SOC are largely externalities shared by the public [23]. Therefore, the benefits of maintaining or increasing SOC sequestration are given mostly to the public who do not pay for this benefit [23]. Markets for SOC (or SC-CO_2) are not self-creating because there is little direct benefit or cost to the farmers for these externalities [23]. Furthermore, these externalities (social costs) are often higher than the marginal cost of farmers [24]. When producers increase carbon sequestration through soil management, they produce a significant public good, but few receive compensation [23]. Individual producers evaluate the benefits of a change in soil management based on on-farm results and may not invest in increasing or maintaining SOC if the cost is higher than their economic benefit [24]. Public investment in SOC level improvement may be warranted because of the critical societal benefits [24]. Policies for SOC management require incentives within administrative boundaries but informed by the geographic distribution of SC-CO_2 [24]. In that way, the most cost-effective management options can be incentivized [23].

5. Conclusions

Carbon sequestered in soils as SOM provides regulating ecosystem services (e.g., carbon sequestration and climate regulation), but its monetary value is often not included in economic valuations of ecosystem services. In this study, the regulating services provided by SOC were valued based on the SC-CO_2 in the contiguous United States (U.S.) (with a midpoint valuation of $12.7T) by soil order, depth, state, region, and land resource region (LRR). Soil orders with the highest (midpoint) values for SOC storage were: (1) Mollisols ($4.21T), (2) Histosols ($2.31T), and (3) Alfisols ($1.48T), whereas Andisols ($113B) and Vertisols ($299B) were the soil orders with the lowest SOC storage values. When normalized by land area, soil orders with the highest (midpoint) SOC values were: (1) Histosols ($21.58 m^{-2}), (2) Vertisols ($2.26 m^{-2}), and (3) Mollisols ($2.08 m^{-2}), while Aridisols ($0.62 m^{-2}) had the lowest area-normalized SOC value. The majority of the SOC value was associated with the 20–100 cm soil depth interval, with a midpoint value of $6.18T and an area-normalized value of $0.84 m^{-2}. The LRRs with the highest (midpoint) values of SOC storage were: (1) M—Central Feed Grains and Livestock Region ($1.8T), (2) T—Atlantic and Gulf Coast Lowland Forest and Crop Region

($1.26T), and (3) K—Northern Lake States Forest and Forage Region ($1.16T), whereas S—Northern Atlantic Slope Diversified Farming Region ($114B) and O—Mississippi Delta Cotton and Feed Grains Region ($158B) were the LRRs with the lowest SOC storage values. States with the highest (midpoint) values for SOC storage were: (1) Texas ($1.08T), (2) Minnesota ($834B), and (3) Florida ($742B) while Rhode Island ($6.93B) and Delaware ($20.6B) had the lowest values. States, when normalized by land area, were ranked as: (1) Florida ($5.44 m^{-2}), (2) Delaware ($4.10 m^{-2}), and (3) Minnesota ($3.99 m^{-2}) while Nevada ($0.51 m^{-2}) and Arizona ($0.59 m^{-2}) had the lowest area-normalized values. The regions with the highest (midpoint) values for SOC storage were: (1) Midwest ($3.17T), (2) Southeast ($2.44T), and (3) Northern Plains ($2.35T), whereas the East region had the lowest value ($914B). Region ranking when normalized by land area were: (1) Midwest ($2.73 m^{-2}), (2) Southeast ($2.31 m^{-2}), and (3) East ($1.82 m^{-2}), while the West region had the lowest land area normalized value ($1.03 m^{-2}).

The total values and area-normalized values of SOC stocks were highly variable due to biogeophysical variation, which limits the maximum feasible SOC sequestration potential. These limits are further impacted by climate change and human soil management decisions. Reported values can be used for allocating the appropriate amount of responsibility for externalities generated by SOC for administrative units that possess greater SOC values. The most cost-effective policies for SOC management need incentives within administrative boundaries but informed by the geographic distribution of SC-CO_2. Future research should examine the use of detailed direct and remotely sensed carbon data in the valuation of regulating ecosystem services provided by the SOC.

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