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Assessing the Value of Soil Inorganic Carbon for Ecosystem Services in the Contiguous United States Based on Liming Replacement Costs

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Abstract: Soil databases are very important for assessing ecosystem services at different administrative levels (e.g., state, region etc.). Soil databases provide information about numerous soil properties, including soil inorganic carbon (SIC), which is a naturally occurring liming material that regulates soil pH and performs other key functions related to all four recognized ecosystem services (e.g., provisioning, regulating, cultural and supporting services). However, the ecosystem services value, or "true value," of SIC is not recognized in the current land market. In this case, a negative externality arises because SIC with a positive value has zero market price, resulting in the market failure and the inefficient use of land. One potential method to assess the value of SIC is by determining its replacement cost based on the price of commercial limestone that would be required to amend soil. The objective of this study is to assess SIC replacement cost value in the contiguous United States (U.S.) by depth (0–20, 20–100, 100–200 cm) and considering different spatial aggregation levels (i.e., state, region, land resource region (LRR) using the State Soil Geographic (STATSGO) soil database. A replacement cost value of SIC was determined based on an average price of limestone in 2014 ($10.42 per U.S. ton). Within the contiguous U.S., the total replacement cost value of SIC in the upper two meters of soil is between $2.16T (i.e., 2.16 trillion U.S. dollars, where T = trillion = 10^{12}) and $8.97T. States with the highest midpoint total value of SIC were: (1) Texas ($1.84T), (2) New Mexico ($355B, that is, 355 billion U.S. dollars, where B = billion = 10^{9}) and (3) Montana ($325B). When normalized by area, the states with the highest midpoint SIC values were: (1) Texas ($2.78 m^{-2}), (2) Utah ($1.72 m^{-2}) and (3) Minnesota ($1.35 m^{-2}). The highest ranked regions for total SIC value were: (1) South Central ($1.95T), (2) West ($1.23T) and (3) Northern Plains ($1.01T), while the highest ranked regions based on area-normalized SIC value were: (1) South Central ($1.80 m^{-2}), (2) Midwest ($0.82 m^{-2}) and (3) West ($0.63 m^{-2}). For land resource regions (LRR), the rankings were: (1) Western Range and Irrigated Region ($1.10T), (2) Central Great Plains Winter Wheat and Range Region ($926B) and (3) Central Feed Grains and Livestock Region ($635B) based on total SIC value, while the LRR rankings based on area-normalized SIC value were: (1) Southwest Plateaus and Plains Range and Cotton Region ($3.33 m^{-2}), (2) Southwestern Prairies Cotton and Forage Region ($2.83 m^{-2}) and (3) Central Great Plains Winter Wheat and Range Region ($1.59 m^{-2}). Most of the SIC is located within the 100–200 cm depth interval with a midpoint replacement cost value of $2.49T and an area-normalized value of $0.34 m^{-2}. Results from this study provide a link between science-based estimates (e.g., soil order) of SIC replacement costs within the administrative boundaries (e.g., state, region etc.).

Keywords: agriculture; calcium; food security; land use; liming; market failure; negative externality; replacement cost method; soil inorganic carbon (SIC); STATSGO

1. Introduction

The United Nations (UN) adopted 17 Sustainable Development Goals to sustain global human societies [1]. Soil ecosystem services are important in achieving some of these goals, for example: "2. End hunger, achieve food security and improve nutrition and promote sustainable agriculture; 3. Ensure healthy lives and promote well-being for all at all ages; 6. Ensure availability and sustainable management of water and sanitation for all; and 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation and biodiversity loss" [1]. These goals can be achieved within the framework of ecosystem services, which includes four main categories: 1. provisioning, 2. regulating, 3. cultural and 4. supporting services [2].

Soil ecosystem services are especially important worldwide because of their provision of food, forage, fiber, bioenergy and pharmaceuticals [3]. The value of ecosystem services can be estimated in various ways, but generally there are three main steps involved: 1. measuring the extent of the ecosystem service, 2. determining the monetary value and 3. designing policy for managing ecosystem services [4]. There is also a slightly different approach to defining the three key stages: 1. ecosystem services, 2. valuation and 3. damage costs [5]. Although significant progress has been made with regard to assessing the value of soil ecosystem services, there is still no clear consensus about which framework and soil properties should be included and how they should be evaluated within the existing frameworks [6,7]. A current list of key soil properties linked to ecosystem services through soil functions for the well-being of humans include: soil organic carbon (SOC); sand, silt, clay and coarse fragments; soil pH; depth to bedrock; bulk density; available water capacity; cation exchange capacity; electrical conductivity; soil porosity and permeability; hydraulic conductivity and infiltration; soil biota; soil structure and aggregation; soil temperature; clay mineralogy; and subsoil pans [2].

According to the current list of soil properties, only soil organic carbon (SOC) has been recognized within the ecosystem services framework, despite the fact that total soil carbon (TC) consists of the sum of SOC and SIC as well as recognition of the dynamics between SOC and SIC reservoirs in terrestrial systems [8,9]. Research has shown that both SOC and SIC are dynamic and rapidly change as a result of land use conversion [8]. Agricultural practices (e.g., irrigation, fertilization, liming etc.) can alter SIC in the soils [10]. Irrigation tends to increase SIC in the soil subsurface horizons [10]. Soil acidification rates in agricultural soils vary by soil type, land use and can be partially offset by application of agricultural lime (aglime) [10]. In the United States nearly 30 Tg (Teragram = 1012 g = 106 metric tonne) of aglime is consumed on an annual basis [11].

It was proposed to include SIC in the ecosystem services framework because it is a major component of the global carbon cycle and is important for many ecosystem services [12]. Soil inorganic carbon is especially important in provisioning services (products, which can be obtained from the ecosystem such as raw materials, food, fuel and fiber), because it is a natural "raw" liming material [13,14]. Calcium associated with SIC is also beneficial to human health and research shows that calcium intake varies by country [15]. Because insufficient calcium intake is a global problem, it is important to assess, monitor and value SIC for sustainable development [15].

Soil inorganic carbon is found in various forms (both disseminated and concentrated forms; e.g., concretions), quantities and depths in different soils [16,17]. Soil inorganic carbon distribution varies by soil type, parent material, climate and land use [9,18]. In general, arid-region soils have high SIC content and humid-region soils have low SIC content [9]. Soil databases provide information about soil inorganic carbon (SIC) distribution with depth, where SIC is reported as $CaCO_3$ (%) by weight in the fraction of the soil less than 2-mm in size [9]. This information is essential in assessing science-based biophysical accounts of this soil property in relation to the ecosystem services (Table 1).

Table 1. Conceptual overview of the SIC accounting framework used in this study.

Biophysical Accounts (Science-based)	Administrative Accounts (Boundary-based)	Monetary Accounts	Benefit	Value
Soil extent:	Administrative extent:	Ecosystem service(s):	Agriculture:	Replacement value:
- Soil order - Soil depth	- Country - State - Land Resource Region (LRR)	- Provisioning (e.g., food) - Commodity	- Liming equivalent - pH buffering	- Price of lime, gypsum

The monetary value of SIC storage and content were assessed (ranked) in the 12 soil orders of Soil Taxonomy within the continental United States (U.S.) using the liming replacement costs [12]. Although, science-based assessment of SIC using soil orders is essential, it can be difficult to interpret this information for policy and decision making which typically is performed at administrative levels (e.g., state, region etc.) (Table 1). This is mainly because the land markets, especially those used for agricultural purposes, do not recognize the monetary value of SIC. In a market with full information, the price of land would simply be an outcome of the interactions between supply and demand. In this case, "full information" would include information about the importance of SIC to soil management. In an idealized market such as this, the price of land (and of goods grown on that land) would already incorporate the value of SIC. At present, however, land markets do not acknowledge or incorporate the value of SIC. The missing price information of SIC has resulted in a market failure. Market forces are determined based on the self-interest of each individual participating in that market. This means, for example, that producers will try to charge as much as they can for their products, while consumers will try to pay as little as they can for the products they want. Current markets do not have a way of assigning a cost or a value to SIC. As a result, the replacement costs of SIC are unlikely to be accounted for in pursuit of individual self-interest, since there is no current SIC valuation. This poses a significant problem, because the loss of SIC can cause a considerable amount of loss at the collective or social level. This is a consequence of the fact that the social cost, which is the real cost of using land, is equal to the private production cost in addition to the cost of replacing SIC. In other words, in cases like this there is a discrepancy between the private and social costs: using up a resource like SIC does not cost very much for individual private farmers, but it imposes a much more significant cost on society in general. This sort of discrepancy between public and private costs is referred to in economics as a "negative externality" [19,20].

Negative externalities can be problematic, as they may result in both inefficient allocation and misuse of important resources (land and soil, in this case) [21]. Moreover, if such negative externalities are not corrected for, they can become even more severe in the long run, eventually resulting in tremendous costs to fix them. In order to address this sort of market failure, one key approach is to use government interventions to "internalize" the externalities in question [22]. In other words, governments can try to motivate producers and consumers to take the externalities into account when deciding what is in their own interest. This can be done by means of either price-based instruments (e.g., taxes, charges, subsidies) or quantity-based instruments (e.g., restrictions on input or output) [23].

In this case, a negative externality arises because SIC has positive value, but zero market price. As such, estimating the replacement cost of SIC is the crucial step to addressing the externality and correcting the market failure. The objective of this study is to assess SIC replacement cost value in the contiguous United States (U.S.) by depth (0–20, 20–100, 100–200 cm) and considering different spatial aggregation levels (i.e., state, region, land resource region (LRR)) using the State Soil Geographic (STATSGO) soil database.

2. Materials and Methods

A monetary valuation of SIC was calculated based on an average U.S. price of $10.42 in the year 2014 per U.S. ton of limestone ($CaCO_3$) [24]. For the continental U.S., values for the minimum, midpoint and maximum SIC storage for all soils by depth (0–20, 20–100, 100–200 cm), state, region and land resource region (LRR) were acquired from [9]. These values were converted to U.S. dollars and dollars per square meter in Microsoft Excel using the following equations:

$$\$ = (SIC\ Storage, g) \times \frac{100\ g\ CaCO_3}{12\ g\ SIC} \times \frac{1\ lb_m}{453.59\ g} \times \frac{1\ U.S.ton}{2000\ lb_m} \times \frac{\$\,price}{U.S.ton\ CaCO_3} \quad (1)$$

$$\$/_{m^2} = (price\ from\ eqn.1) \times \frac{1}{area\ in\ km^2} \times \frac{1\ km^2}{10^6\ m^2} \quad (2)$$

For example, the State of Iowa has an area of 143,801 km^2 and a midpoint SIC storage of 167,537 × 10^4 Mg, where Mg is megagrams of carbon [9]. In terms of grams, the SIC storage would be expressed as 1.675 × 10^{15} g. Using this value for SIC storage in the first equation together with the average price of agricultural limestone in the U.S, which according to the U.S. Geological Survey (USGS) was $10.42 per U.S. ton in 2014 [24], results in a value of 1.60 × 10^{11} U.S. dollars or 160 billion U.S. dollars ($160B). With the second equation, the midpoint value of SIC normalized by area is $1.12 m^{-2} for the State of Iowa.

Note that the price values calculated in U.S. dollars and dollars per square meter represent the money that would be required simply to purchase agricultural limestone to match the naturally-occurring SIC levels. The values reported would not cover other important costs, such as the equipment, fuel and labor that would be required to incorporate the limestone into the soil nor any external costs associated with mining the limestone and so forth.

3. Results and Discussion

Soil inorganic carbon naturally occurring in the soil provides a substantial monetary value to the U.S. and it was evaluated using three key stages: 1. ecosystem services, 2. valuation, 3. damage/replacement costs [5]. The replacement values of SIC varies by soil order, depth, state, region and LRR. Soil inorganic carbon replacement costs/values were shown as minimum (min), midpoint (mid) and maximum (max). Estimated values from STATSGO min, mid and max can be used to represent the uncertainty in replacement cost estimates [25]. It has been demonstrated that the min and max values for a number of soil properties (e.g., clay content, pH, organic carbon content, pH) were similar to the 95% prediction intervals from a data derived from multiple soil profiles [25].

Recent research proposed inclusion of SIC into the ecosystem services framework for the United Nations Sustainable Development Goals [12]. It was reported that the soil orders having the highest total midpoint value of SIC storage for the U.S. (based on the average replacement cost of $10.42 per ton of $CaCO_3$) were: (1) Mollisols ($2.22T), (2) Aridisols ($1.23T), (3) Alfisols ($523B) and (4) Entisols ($489B). For SIC on an area basis, they ranked the soil orders as: (1) Vertisols ($2.22 m^{-2}), (2) Aridisols ($1.52 m^{-2}), (3) Mollisols ($1.10 m^{-2}) and (4) Inceptisols ($0.49 m^{-2}) [12]. These soil orders range from slightly-weathered to moderately-weathered soils in the Midwest and western regions of the country. There are several reasons for SIC accumulations in these soils including geographic locations with semi-arid and arid climates and calcium-rich parent materials [12]. In contrast, the soil orders having the lowest total midpoint value of SIC storage for the U.S. were Spodosols, Ultisols and Oxisols [12]. These soils are located primarily in the eastern half of the continental U.S. and humid tropical islands. These geographic locations tend to have humid climates which result in highly-leached soils with low SIC accumulations [12].

3.1. The Value of SIC at Country Scale by Soil Sampling Depth

Total SIC storage at 0–20 cm, 20–100 cm and 100–200 cm depths intervals represents the total amount of SIC shown as minimum (min), midpoint (mid) and maximum (max) (Table 2). The highest replacement cost value of SIC storage is found in the 100–200 cm depth interval. The lowest replacement cost value of SIC storage is found in the agriculturally important surface depth of 0–20 cm (Table 2).

Table 2. Total SIC value and area-averaged value by depth for the contiguous United States based on [9] and a 2014 U.S. average price of $10.42 per U.S. ton of agricultural limestone [24].

Depth (cm)	-------------- Total Value --------------			-------- Value per Area --------		
	Min. ($)	**Mid. ($)**	**Max. ($)**	**Min. ($ m^{-2})**	**Mid. ($ m^{-2})**	**Max. ($ m^{-2})**
0–20	1.72E+11	3.92E+11	6.80E+11	0.02	0.05	0.09
20–100	9.76E+11	2.30E+12	3.96E+12	0.13	0.31	0.54
100–200	1.01E+12	2.49E+12	4.34E+12	0.14	0.34	0.59
Totals	**2.16E+12**	**5.18E+12**	**8.97E+12**			

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

Soil inorganic carbon replacement cost value per square meter represents the area density of SIC within the country (Table 2). The highest replacement cost value of SIC is found in the 100–200 cm depth interval. The lowest replacement cost value of SIC is found in the agriculturally important surface depth of 0–20 cm.

3.2. The Value of SIC at Country Scale by Land Resource Regions (LRR)

Land resource regions (LRRs) are defined by United States Department of Agriculture as geographically associated major land resource areas (MLRAs) which include broad agricultural market regions and are designated by capital letters (e.g., A, B C, etc.). There are 28 total land resource regions, but in this study Table 3 contains information only for 20 since the study is limited to the contiguous U.S. The LRRs with the highest midpoint total replacement cost value of SIC storage were: (1) D—Western Range and Irrigated Region ($1.10T), (2) H—Central Great Plains Winter Wheat and Range Region ($926B) and (3) M—Central Feed Grains and Livestock Region ($635B). On an area basis, the highest replacement cost values were: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($3.33 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region ($2.83 m^{-2}) and (3) H—Central Great Plains Winter Wheat and Range Region ($1.59 m^{-2}) (Table 3, Figure 1). The LRRs with the highest mean replacement cost values per area over the depth interval 0–20 cm were: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($0.43 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region ($0.27 m^{-2}) and (3) D—Western Range and Irrigated Region ($0.11 m^{-2}) (Table 3, Figure 1). Over the depth interval 0–100 cm, the highest mean replacement cost values were: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($1.86 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region (1.49m^{-2}$) and (3) F—Northern Great Plains Spring Wheat Region ($0.70 m^{-2}).

Table 3. Total SIC value and area-averaged value for Land Resources Regions (LRRs) based on [9] and a 2014 U.S. average price of $10.42 per U.S. ton of agricultural limestone [24].

LRRs	Area (km^2)	---------------- Total Value ---------------			------- Value per Area ------		
		Min. ($)	**Mid. ($)**	**Max. ($)**	**Min. ($ m^{-2})**	**Mid. ($ m^{-2})**	**Max. ($ m^{-2})**
A	181,215	6.70E+06	1.59E+08	4.46E+08	0.00	0.00	0.00
B	259,284	9.11E+10	1.96E+11	3.32E+11	0.35	0.76	1.28
C	146,884	2.06E+09	5.73E+09	9.87E+09	0.01	0.04	0.07
D	1,268,922	4.88E+11	1.10E+12	1.88E+12	0.38	0.87	1.48
E	521,994	8.51E+10	1.85E+11	3.25E+11	0.16	0.35	0.62
F	351,842	1.66E+11	4.01E+11	6.99E+11	0.47	1.14	1.99
G	521,442	1.47E+11	3.53E+11	5.98E+11	0.28	0.68	1.15
H	583,820	4.25E+11	9.26E+11	1.54E+12	0.73	1.59	2.63
I	169,689	2.41E+11	5.65E+11	9.84E+11	1.43	3.33	5.80
J	139,624	2.03E+11	3.96E+11	6.29E+11	1.45	2.83	4.51
K	300,269	5.61E+10	1.89E+11	3.68E+11	0.19	0.63	1.23

L	119,997	5.58E+10	1.34E+11	2.38E+11	0.47	1.12	1.98
M	717,615	1.77E+11	6.35E+11	1.19E+12	0.25	0.88	1.66
N	603,434	7.49E+08	5.14E+09	1.13E+10	0.00	0.01	0.02
O	94,652	3.27E+09	1.90E+10	3.86E+10	0.04	0.20	0.41
P	677,160	1.44E+09	4.65E+09	8.50E+09	0.00	0.01	0.01
R	300,536	8.82E+08	7.33E+09	1.72E+10	0.00	0.03	0.06
S	99,147	0.00E+00	6.22E+07	2.04E+08	0.00	0.00	0.00
T	231,303	1.60E+10	5.23E+10	9.65E+10	0.07	0.23	0.42
U	85,410	4.61E+09	8.10E+09	1.24E+10	0.06	0.10	0.14
Totals	**7,374,239**	**2.16E+12**	**5.18E+12**	**8.97E+12**			

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.

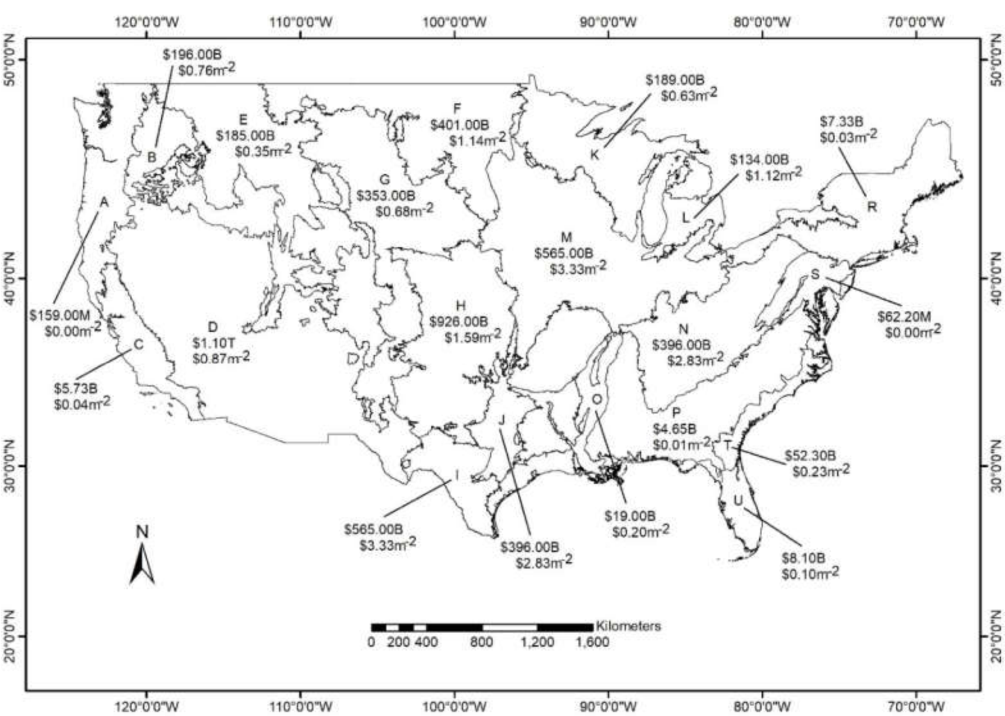

Figure 1. The midpoint replacement cost value of SIC for total storage (top number) and value normalized by area (bottom number) for different Land Resources Regions (LRRs) in the contiguous United States based on [9] and a 2014 average price for limestone of $10.42 per U.S. ton [24].

3.3. The Value of SIC at Country Scale by State

States with the highest midpoint total replacement cost value of SIC storage were: (1) Texas ($1.84T), (2) New Mexico ($355B, that is, 355 billion U.S. dollars) and (3) Montana ($325B) (Table 4).

On an area basis, the highest midpoint replacement cost values were: (1) Texas (\$2.78 m^{-2}), (2) Utah (\$1.72 m^{-2}) and (3) Minnesota (\$1.35 m^{-2}) (Figure 2).

Table 4. Total SIC value and area-averaged value (rankings) of each state (region) based on [9] and a 2014 U.S. average price of \$10.42 per U.S. ton of agricultural limestone [24].

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	1.34E+07	8.04E+07	1.91E+08	0.00	0.01	0.02
Delaware	5043	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Massachusetts	18,918	9.57E+05	5.07E+07	1.24E+08	0.00	0.00	0.01
Maryland	25,266	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Maine	80,584	1.91E+07	7.37E+07	1.49E+08	0.00	0.00	0.00
New Hampshire	22,801	0.00E+00	7.66E+06	1.82E+07	0.00	0.00	0.00
New Jersey	17,788	9.57E+05	4.50E+07	1.07E+08	0.00	0.00	0.01
New York	118,432	2.22E+09	1.45E+10	3.33E+10	0.02	0.12	0.28
Pennsylvania	115,291	0.00E+00	3.07E+08	8.54E+08	0.00	0.00	0.01
Rhode Island	2583	0.00E+00	1.91E+06	4.79E+06	0.00	0.00	0.00
Vermont	23,764	2.52E+08	1.26E+09	2.82E+09	0.01	0.06	0.11
West Virginia	61,448	5.07E+07	2.42E+08	4.52E+08	0.00	0.00	0.01
(East)	504,325	**2.56E+09**	**1.66E+10**	**3.81E+10**	**0.01**	**0.03**	**0.08**
Iowa	143,801	3.84E+10	1.60E+11	3.01E+11	0.27	1.12	2.10
Illinois	143,948	1.42E+10	1.03E+11	2.13E+11	0.10	0.72	1.48
Indiana	93,584	3.37E+10	1.06E+11	1.97E+11	0.36	1.13	2.11
Michigan	147,532	7.13E+10	1.72E+11	3.05E+11	0.48	1.17	2.07
Minnesota	209,223	1.06E+11	2.83E+11	5.01E+11	0.51	1.35	2.39
Missouri	177,484	2.53E+09	2.05E+10	4.13E+10	0.01	0.11	0.23
Ohio	105,442	2.03E+10	6.34E+10	1.19E+11	0.19	0.60	1.13
Wisconsin	140,542	1.09E+10	5.28E+10	1.12E+11	0.08	0.37	0.79
(Midwest)	1,161,556	**2.97E+11**	**9.60E+11**	**1.79E+12**	**0.26**	**0.82**	**1.54**
Arkansas	135,832	5.42E+08	4.45E+09	9.32E+09	0.00	0.03	0.07
Louisiana	109,273	3.91E+09	1.68E+10	3.32E+10	0.04	0.15	0.31
Oklahoma	176,647	3.94E+10	8.92E+10	1.49E+11	0.22	0.51	0.84
Texas	660,649	8.31E+11	1.84E+12	3.10E+12	1.25	2.78	4.70
(South Central)	1,082,402	**8.74E+11**	**1.95E+12**	**3.29E+12**	**0.80**	**1.80**	**3.04**
Alabama	130,948	1.90E+08	3.35E+08	5.03E+08	0.00	0.00	0.00
Florida	136,490	4.61E+09	8.20E+09	1.26E+10	0.04	0.06	0.10
Georgia	149,285	3.63E+08	1.07E+09	1.92E+09	0.00	0.01	0.01
Kentucky	101,847	3.26E+08	1.40E+09	2.61E+09	0.00	0.01	0.03
Mississippi	122,583	0.00E+00	3.26E+09	7.38E+09	0.00	0.03	0.06
North Carolina	125,522	0.00E+00	6.41E+07	1.42E+08	0.00	0.00	0.00
South Carolina	78,489	4.91E+08	1.42E+09	2.53E+09	0.01	0.02	0.03
Tennessee	104,277	2.87E+06	3.05E+08	6.84E+08	0.00	0.00	0.01
Virginia	102,714	0.00E+00	2.03E+08	4.48E+08	0.00	0.00	0.00
(Southeast)	1,052,154	**5.98E+09**	**1.63E+10**	**2.88E+10**	**0.01**	**0.02**	**0.03**
Colorado	253,888	4.85E+10	1.38E+11	2.45E+11	0.19	0.55	0.97
Kansas	212,325	5.20E+10	9.62E+10	1.47E+11	0.25	0.45	0.69
Montana	350,837	1.56E+11	3.25E+11	5.50E+11	0.44	0.93	1.57
North Dakota	178,589	6.47E+10	1.74E+11	3.12E+11	0.36	0.98	1.74
Nebraska	198,419	8.62E+09	4.77E+10	9.27E+10	0.05	0.24	0.47
South Dakota	191,914	3.85E+10	1.02E+11	1.77E+11	0.20	0.53	0.93
Wyoming	229,275	5.30E+10	1.27E+11	2.17E+11	0.23	0.56	0.95

(Northern Plains)	1,615,247	**4.21E+11**	**1.01E+12**	**1.74E+12**	**0.26**	**0.62**	**1.08**
Arizona	266,867	6.43E+10	1.87E+11	3.42E+11	0.24	0.70	1.28
California	353,973	1.48E+10	3.84E+10	7.19E+10	0.04	0.11	0.20
Idaho	197,155	6.72E+10	1.53E+11	2.69E+11	0.34	0.78	1.37
New Mexico	284,358	1.70E+11	3.55E+11	5.86E+11	0.60	1.25	2.06
Nevada	269,415	4.67E+10	1.04E+11	1.81E+11	0.17	0.38	0.67
Oregon	239,876	1.42E+10	2.99E+10	4.96E+10	0.06	0.12	0.21
Utah	185,030	1.63E+11	3.18E+11	5.07E+11	0.88	1.72	2.74
Washington	161,881	2.26E+10	4.54E+10	7.33E+10	0.14	0.28	0.45
(West)	1,958,556	**5.63E+11**	**1.23E+12**	**2.08E+12**	**0.29**	**0.63**	**1.06**
Totals	**7,374,238**	**2.16E+12**	**5.18E+12**	**8.97E+12**			

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

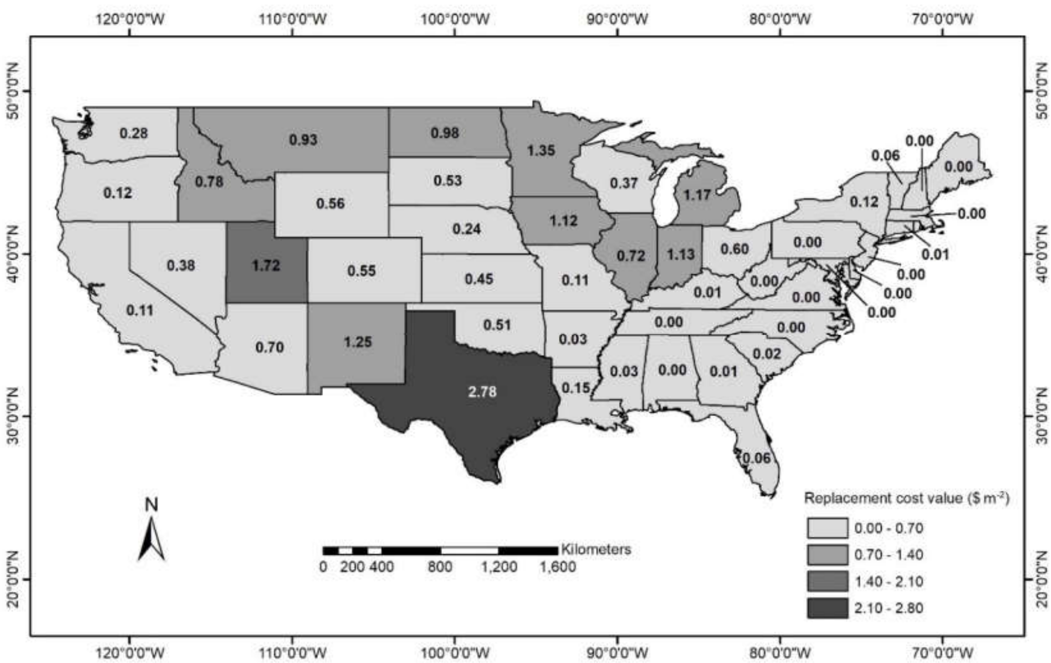

Figure 2. The midpoint replacement cost value ($ m^{-2}) of SIC in the contiguous United States based on [9] and a 2014 average price for limestone of $10.42 per U.S. ton [24].

3.4. The Value of SIC at Country Scale by Region

The regions with the highest midpoint total replacement cost value of SIC storage were: (1) South Central ($1.95T), (2) West ($1.23T) and (3) Northern Plains ($1.01T) (Table 4). On an area basis, the regions were ranked: (1) South Central ($1.80 m^{-2}), (2) Midwest ($0.82 m^{-2}) and (3) West ($0.63 m^{-2}) (Figure 3).

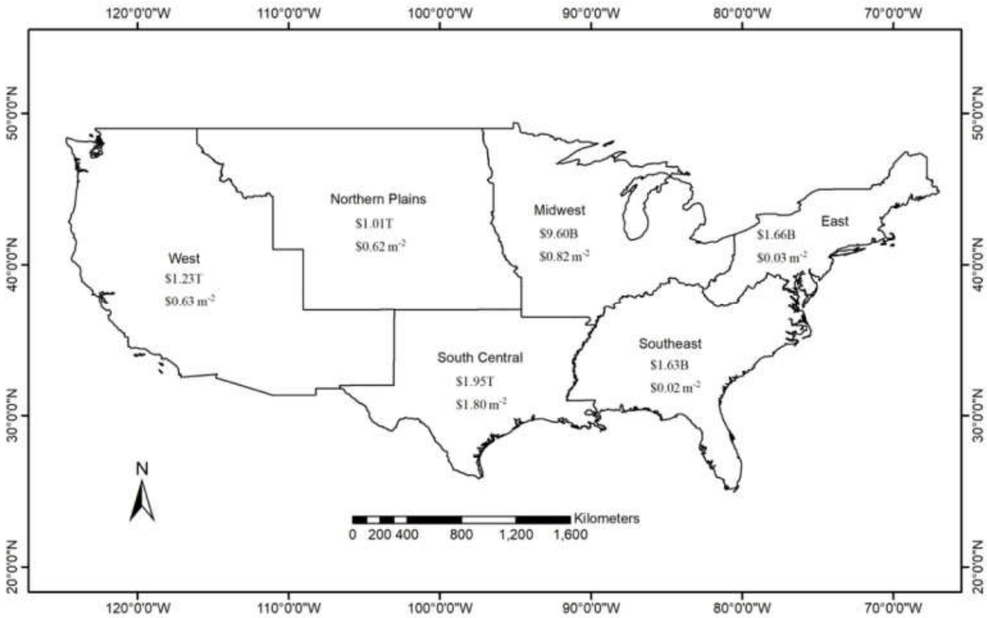

Figure 3. The midpoint replacement cost value of SIC for total storage (top number) and value normalized by area (bottom number) for different regions in the contiguous United States based on [9] and a 2014 average price for limestone of $10.42 per U.S. ton [24].

3.5. Implications for Ecosystem Services and Sustainable Development Goals (SDGs)

Inclusion of SIC into the list of key soil properties linked to ecosystem services through soil functions for the well-being of humans is important for achieving the SDGs to sustain global human societies [1]. First of all, SIC is a component of TC, which is composed of both SOC and SIC [26]. Soil inorganic carbon belongs to soil chemical properties, and its soil functions include cycling of elements (e.g., Ca^{2+}), elemental transformation, buffering (e.g., soil pH) and leaching (e.g., bicarbonates) [26]. The significance of SIC in agriculture (especially as a liming equivalent) is well documented [27] and the following examples are specifically linked to the selected SDGs [1]:

2. End hunger, achieve food security and improve nutrition and promote sustainable agriculture;

Naturally present SIC includes numerous beneficial liming impacts on soils such as increased nutrients and biota, improved soil structure [28], which promotes sustainable agriculture and food security. Calcium in SIC contributes to increased yield of grain and biomass (often through impacts on nutrient cycling) which has direct implications for food security [27]. Grasslands biomass and nutrients increase which improves livestock growth and therefore food production (as shown through liming addition studies) [27].

3. Ensure healthy lives and promote well-being for all at all ages;

Soil is a supplier of macro- and micronutrients necessary for human health [26]. Soil inorganic carbon is a source of macronutrients (e.g., calcium and magnesium) which are essential for human health.

6. Ensure availability and sustainable management of water and sanitation for all;

Soil inorganic carbon can likely counteract acid deposition thereby protecting water quality and may reduce NO_3^- leaching [27].

15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation and biodiversity loss.

Highest species richness often is highest in pH-neutral soils and falls significantly below a pH of 5 [27]. Soil calcium availability from SIC-rich soils may positively impact higher trophic levels, with initial evidence that some birds may benefit as shown through liming studies [27].

Although significant progress has been made in documenting the importance of various soil properties, the economic valuation of ecosystems services remains a hurdle because the understanding of various related soil functions under different land use is still poorly understood [6].

3.6. Economic Implications

With information on the replacement costs of SIC, governments can play a role in correcting for the market failure that results from the lack of market pricing for SIC. In essence, as the price of SIC is zero in the market, the government should compensate by imposing a cost on SIC, so that it will be taken into account during decision-making about agricultural production.

Taxing the land users is the most commonly used instrument in this sort of government intervention, although determining the optimal rate for such a tax would be challenging. Ideally, a Pigouvian tax [29] can be used to correct an inefficient market failure caused by a negative externality, thereby encouraging a more efficient allocation of the resource. Theoretically, a Pigouvian tax schedule is set equal to the social cost of the negative externality. In this case, it would equate the tax rates to the replacement costs of SIC which would be used to reduce the negative externality and to help encourage a more efficient allocation of the resource. A Pigouvian tax of this sort would also vary rates across different locations (i.e., states and regions in this case), in order to better reflect the different replacement costs of SIC in those locations. Such an approach is impractical, however, because it would be too costly to design and implement. Alternatively, a quasi-Pigouvian tax, set below the market equilibrium level, would likely reduce the negative externality with marginal improvements in efficiency, which would decrease as the tax rate approaches the optimal market level. On this approach, the tax rate could be periodically revised, when more information about the markets and the value of SIC becomes available.

If such a tax were imposed, one significant question is who should pay the tax. Although taxes are initially collected from the land users (mainly food producers), they may be eventually transferred or partially transferred to food consumers, who would end up paying higher prices for food they purchase, due to the taxes imposed on land users. If the demands for agricultural products were elastic (i.e., if the demands are sensitive to the price changes), then producers would bear most of the cost increases. If the agricultural products were inelastic (i.e., if the demands are not sensitive to the price changes), then consumers would bear most cost increases. Another controversial issue associated with such a tax is how the government should spend the collected revenue. Allocating this revenue to encourage sustainable land use and to address decreasing stocks of SIC would likely make such a tax more acceptable to the community.

When having a tax schedule is too costly or not legally feasible, governments may also improve land market efficiency by using policy regulations, such as setting up laws or standards to ensure the certain SIC stocks in the soil. This kind of policy regulation would only work if SIC stocks were easy and not expensive to measure, however. When addressing a market failure in this way, the costs of government actions (such as administration, monitoring and enforcement) should also be accounted for. Put simply, governments should only intervene to address a negative externality when the benefits of such an intervention are expected to outweigh the total costs to the government of implementing that intervention.

4. Conclusions

Fertile soils often contain appreciable amounts of SIC, which can be considered a naturally occurring liming material, but it has not been included in economic valuations of ecosystem services. The amount of this naturally occurring liming material varies by soil order, parent material, climate and land use. Although the SIC has been valued by soil order within the contiguous U.S., this type of analysis has limited application to decision making, because decisions are made using administrative levels. Soil databases contain science-based information about soil properties (based on soil taxonomy) which are of great importance in assessing ecosystem services at different administrative levels (e.g., state, region etc.). The SIC replacement cost/value in the contiguous United States (U.S.) varies by depth, state, region and land resource region (LRR) because of soil type, land use and climate. This spatial distribution information could be linked to existing or future policy with regards to sustainable soil nutrient management. The fact that SIC has positive value but zero market price results in the negative externality and the inefficient use of land. Estimating the replacement cost of SIC is the crucial step to correcting the market failure. The results of this study provide a link between science-based estimates of SIC and market-based replacement costs within the administrative boundaries. Future research on SIC and ecosystems services should combine spatial and temporal variation in SIC replacement costs or other methods of valuation. Another important future research consideration is understanding supply and demand for SIC ecosystem services to meet the SDGs.

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