Accounting for soil inorganic carbon in the ecosystem services framework for United Nations sustainable development goals

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ABSTRACT

Soil inorganic carbon (SIC) is currently not included in the list of key soil properties related to ecosystem services (e.g., provisioning, regulating, cultural, and supporting services). Soil inorganic carbon is a dynamic key soil property used in soil classification, taxonomy and fertility, therefore its inclusion in the framework of ecosystem services is important. With soils rapidly changing due to human use and climate change, the ecosystem services framework should include not only soil organic carbon (SOC), but SIC as well since it is of global importance to soil fertility and the long-term carbon (C) cycle, especially in semiarid and arid climates where SIC comprises the largest C pool. The objective of this study is to assess the value of SIC in the 12 soil orders of Soil Taxonomy at the country scale (continental United States (U.S.)) and at the farm scale (the Cornell University Research Farm) within the context of ecosystem services, specifically provisioning and supporting services. At the country scale, the total estimated midpoint value of SIC storage within the upper two meters of soil is $5.17T (i.e., 5.17 trillion U.S. dollars). The soil orders having the highest total value of SIC storage (based on an average 2014 price of $10.42 per U.S. ton of $CaCO_3$ lime in the U.S.) are: 1) Mollisols ($2.22T), 2) Aridisols ($1.23T), 3) Alfisols ($523B, i.e., 523 billion U.S. dollars), and 4) Entisols ($489B). In terms of SIC content (i.e., value per square meter), the soil orders are ranked: 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}). At the farm scale, based on variable measured and reported soil sample depths, the soil orders having the highest total value of SIC (based on an average 2014 price of $10.88 price per U.S. ton of $CaCO_3$ for the State of New York (NY)) were: 1) Alfisols, 2) Inceptisols, and 3) Entisols. However, the farm-scale estimates varied greatly depending on whether the values were based on field-derived vs. SSURGO-derived data. The results of this study begin to provide an estimated value of the importance of SIC when assessing ecosystem services. The potential impacts on society from this research include adding SIC into the ecosystem services framework for the United Nations (UN) Sustainable Development Goals. Future research should identify and quantify other important ecosystem services that SIC may provide on a variety of spatial and temporal scales, as well as the potential need of including total C (TC) and interactions between SIC and SOC pools.

Keywords: agriculture, calcium, food security, land use, liming, pedogenic carbonates (PC), soil inorganic carbon (SIC)

1. Introduction

Soil inorganic carbon (SIC) is a part of total carbon (TC) in soils, however, it is currently not included with the key soil properties related to ecosystem services (e.g. provisioning, regulating, cultural, and supporting services) (Fig. 1). Soil inorganic carbon is an integral part of terrestrial carbon, which can either be a source or sink of carbon (C).

The United Nations (UN) adopted 17 Sustainable Development Goals as guidelines to enhance the sustainability of global human societies (Keesstra et al., 2016). Soil functions are critical to the United Nations Sustainable Development Goals because soils provide clean water, clean air, and food for global societies (Keesstra et al, 2016). The UN Sustainable Development Goals that relate to soil functions include: "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, 13. Take urgent action to combat climate change and its impacts, 15. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (Keesstra et al, 2016).

Ecosystem services exemplify how the ecosystem benefits society through commodities and services (Costanza et al., 2014). Ecosystem services are broken down into four main categories: 1. provisioning services (food, fuel and fiber, raw materials, gene pool, fresh water / water retention), 2. regulating services (climate and gas regulation, water regulation, erosion and flood control, pollination / seed dispersal, pest and disease regulation, carbon sequestration, water purification), 3. cultural services (recreation / ecotourism, esthetic / sense of place, cultural heritage), and 4. supporting services (weathering / soil formation, nutrient cycling, provisioning of habitat) (Adhikari and Hartemink, 2016). The ecosystem services that relate to soil properties of organic carbon include provisioning services: food, fuel, and fiber, raw materials, and fresh water / water retention; regulating services: climate and gas regulation, water regulation, erosion and flood control, pest and disease regulation, carbon sequestration, and water purification; cultural services: recreation/ecotourism, esthetic/sense of place, and knowledge/education/inspiration; supporting services: weathering/soil formation, nutrient cycling, and provisioning of habitat (Adhikari and Hartemink, 2016).

Total carbon (TC) represents the summation of soil inorganic carbon (SIC) and soil organic carbon (SOC) in a terrestrial soil environment. Presently, SOC is included into the ecosystem services framework; however, SIC is not included, despite SIC's contribution within the ecosystem services framework (Keesstra et al., 2016). The exclusion of SIC from the ecosystem services framework stems from the initial supremacy placed on SOC as the driver for soil fertility and its existence as a super colloid. Soil inorganic carbon is a major component of the global carbon cycle and is found in various forms such as, gaseous $CO_{2\,(g)}$, dissolved $CO_{2\,(aq)}$, carbonic acid $H_2CO_{3\,(aq)}$, bicarbonate $HCO_3^-{}_{(aq)}$, carbonate $CO_3^{2-}{}_{(aq)}$, and solid-phase carbonate (primarily $CaCO_3$) (Monger, 2014; Zamanian et al., 2016). Soil inorganic carbon forms, bicarbonate and carbonate, together comprise a larger terrestrial carbon pool than SOC (Monger et al., 2015). Furthermore, solid-phase calcium carbonate is divided two types: lithogenic carbonate and pedogenic carbonate (Monger et al., 2015). Lithogenic carbonates are formed in a marine environment and can be found as fragments in a terrestrial setting (Monger et al., 2015). Pedogenic carbonates are formed authigenically in a soil environment that is commonly under alkaline, arid conditions (Monger et al., 2015).

Soil inorganic carbon provides a significant contribution to ecosystem services, but it is currently overlooked. The objective of this study is to assess the value of SIC in the 12 soil orders of Soil Taxonomy at the country scale (the continental United States) and at farm scale (the Cornell University Research Farm) within the context of ecosystem services, specifically provisioning and supporting services.

2. Soil inorganic carbon and Soil Taxonomy

Soil inorganic carbon has a variable distribution in the U.S. by soil order and depth. Using the State Soil Geographic Database (STATSGO), Guo et al. (2006) reported that half of the 12 soil orders in the conterminous U.S. have appreciable accumulations of SIC and ranked the soil orders by midpoint SIC storage in the following order: (1) Mollisols, (2) Aridisols, (3) Alfisols, (4) Entisols, (5) Inceptisols, and (6) Vertisols. Soils with "slight" and "intermediate" degrees of weathering tend to have more carbonates, whereas soils with a "strong" degree of weathering tend to have little to no accumulations of SIC. Mollisols, Alfisols and Vertisols are important soil orders globally due to high soil productivity for world crops (Liu et al., 2012). Soil inorganic carbon accumulations are identified at the suborder level (e.g. Calcids, Durids, Gypsids, etc.), and by lowercase letter symbols to designate subordinate distinctions within master horizons (e.g., k=accumulation of carbonates, c=concretions or nodules, etc.) (Soil Survey Staff, 2014). Uncertainty associated with STATSGO reported values for SIC is unknown, however Zong et al. (2011) reported that there were significant differences in soil organic matter (SOM) values when comparing STATGO to the more detailed SSURGO databases. Zong et al. (2011) concluded that the SSURGO values for SOM more closely matched field data and were more likely more accurate. This indicates that relying on STATGO for SIC estimates (Guo et al., 2006) can introduce an unknown quantity of error.

The spatial and vertical distribution of SIC is influenced by the amount of rainfall, which tends to decrease from east to west in the U.S. with more carbonate-rich soils found in the western part of the country. Because agricultural activity is influenced by soil pH and naturally available SIC (liming material), early agricultural exploration was driven somewhat from the east coast to the west by the search of naturally neutral and fertile soils (Richter et al., 2001). Additionally, Goddard et al. (2009) reported significant formation of SIC as a result of atmospheric wet calcium deposition (including from aeolian sources) with as much as 2.6×10^8 kg C as SIC was estimated to be formed over a 9 year period barring losses from deep leaching and erosion.

3. Soil inorganic carbon and ecosystem services

3.1. Provisioning services

Provisioning services refer to the products, which can be obtained from the ecosystem such as raw materials, food, fuel, and fiber (Millennium Ecosystem Assessment, 2005). Soil inorganic carbon is a natural “raw” liming material (found in both disseminated and concentrated forms; e.g., concretions) and is important in food, fuel, and fiber production (Tables 1, 2) due to its influence on the soil pH (regulation of nutrient availability) (West and Bride, 2005; Mikhailova et al., 2006; Schaffner et al., 2012). Soil inorganic carbon is also beneficial to human health since “adequate calcium intake is critical for good health and may reduce risks for certain chronic disease” (Wang and Li, 2007). Calcium intake inadequacy is a worldwide problem and many countries, such as India and China, have been increasing dairy production (Wang and Li, 2007). Calcium intake varies by country, for example, average daily calcium intake is 962 mg for U.S. men, and 756 mg for U.S. women in 1999-2004 (Wang and Li, 2007). If every person had access to the recommended 1g/day of calcium (the total daily requirement for the world), with a population of 7.5 billion people (2017), the total results in 7500 metric tons/day. Insufficient calcium intake is a global problem (Wang and Li, 2007), and it is important to assess, monitor and value SIC for sustainable development. Increased demand for food production and biofuels increased nutrient and alkalinity removal as documented by studies in the U.S. Midwest (Avila-Segura et al., 2011), and export of alkalinity via rivers (Raymond, 2003).

Soil inorganic carbon is found in various forms, quantities and depths in different soils. For example, disseminated carbonates and pedogenic carbonate concretions were reported in the Chernozem, common soils in the bread-basket regions of Russia and Ukraine (Mikhailova et al., 2006; Mikhailova and Post, 2006). Soil inorganic carbon is also important for water retention since naturally “limed” soils have better soil structure and rates of infiltration compared to natural acidic soils (USDA/NRCS, 1999). Petrocalcic horizons can have high water-holding capacity, which can be a potential source of water for plants during droughts (Duniway et al., 2007), which contributes to greater resilience of arid ecosystems (Duniway et al., 2010).

3.2. Regulating services

Regulating services refers to the benefits derived from the regulation of processes in the ecosystem such as climate regulation, carbon sequestration, and water purification (Millennium Ecosystem Assessment, 2005). Soil inorganic carbon is important to climate regulation considering the gas exchange between terrestrial $CaCO_3$ (pedogenic carbonate) and atmospheric CO_2 (Zamanian, 2016). Pedogenic carbonate can either sequester atmospheric carbon (ecosystem service) during precipitation or release carbon to the atmosphere during dissolution (ecosystem disservice) (Monger et al., 2015, Zamanian, 2016). For example, when one mole of calcium reacts with two moles of atmospheric CO_2, one mole of carbon is released back into the atmosphere, resulting in one mole of carbon is sequestered in the form of pedogenic carbonate (Monger et al., 2015). In addition, the dissolution of SIC can act as a natural buffer against water or soil acidity in the pedosphere and hydrosphere (Berner and Berner, 1996). For instance, soil inorganic carbon contiguous with a body of water, such as a lake, will regulate the water's pH through natural buffering (Berner and Berner, 1996). The dissolution of SIC can expedite erosion, causing surface collapse (Salvati and Sasowsky, 2002). When soil inorganic carbon buffers acidity in pedosphere and hydrosphere, alkalization occurs. Alkalization from soil inorganic carbon can naturally promote water purification (Berner and Berner, 1996).

3.3. Cultural services

Cultural services refer to the nonmaterial benefits derived from ecosystem services such as recreation, esthetics, education, and cultural heritage (Millennium Ecosystem Assessment, 2005). Globally, Aridisols and Entisols approximately contain 800 x 1015 grams of carbon in caliché layers, unique features of the desert ecosystems (Schlesinger, 1982). Arizona-Sonora Desert Museum in Tuscon provides visitors with opportunities to learn about desert soils as they relate to providing habitat for animals and growing media for desert plants (Arizona-Sonora Desert Museum, 2017). Duniway et al. (2010) reported the importance of carbonate-cemented soil horizons for vegetation patterns and dynamics in arid and semiarid environments.

3.4. Supporting services

Supporting services refers to the benefits that are essential for all other ecosystem services such as weathering/soil formation, nutrient cycling and provisioning of habitat (Millennium Ecosystem Assessment, 2005). Weathering of a siliceous rock or dissolution of a preexisting carbonate are needed for the precipitation of pedogenic carbonate; for instance, calcium ions needed for carbonate precipitation can be sourced from calcium containing igneous rocks that have weathered (Monger et al., 2015). The process of weathering is important for the precipitation of pedogenic carbonate; for instance, calcium ions needed for carbonate precipitation can be from the weathering and erosion of calcareous or siliceous parent material (Monger, 2015). Also, high densities of pedogenic carbonate can be found in areas with strong weathering of calcareous parent material. In addition, weathering processes allow pedogenic carbonates to be natural providers of essential plant nutrients to the soil solution (Lal et al., 2000). For example, mineral weathering of calcite ($CaCO_3$) and dolomite $CaMg(CO_3)_2$ can supply both calcium (Ca^{2+}) ions and magnesium ions (Mg^{2+}) to soil solution (Lal et al., 2000). The calcium and magnesium ions weathered from soil carbonates are in available forms for plant uptake. Soil carbonates in the form of calcite can also be formed from the oesophageal glands of earthworms (Canti et al., 2015).

The objective of this study is to assess the value of SIC: 1) at the country scale (in 12 soil orders of Soil Taxonomy within the continental United States) and 2) at the farm scale (Cornell University Willsboro Research Farm) within the context of ecosystem services, specifically provisioning and supporting services.

4. Materials and methods

For the continental U.S., values for the minimum, midpoint, and maximum SIC storage and content for all soil orders (2-m soil depth) were acquired from Guo et al. (2006). These values were converted to U.S. dollars and dollars per square meter in Microsoft Excel using the following equations:

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

$$\$/m^2 = \left(price\ from\, eqn.1\right) \times \frac{1}{area\, in\, km^2} \times \frac{1\, km^2}{10^6\, m^2} \qquad (2)$$

For example, Guo et al. (2006) reported for Entisols an area of 1,054,015 km^2, a midpoint SIC storage of 5112×10^6 Mg (i.e., megagrams of carbon), and a midpoint SIC content of 4.8 kg m^{-2}. Note that various researchers report carbon storage with different units; here the SIC storage of 5112×10^6 Mg for Entisols also can be expressed equivalently as 5112×10^{12} g, 5112 Tg (teragrams), or 5.112 Pg (petagrams). Using 5112×10^{12} g for SIC storage in eqn. (1) 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 (USGS, 2016), results in a value of 4.89×10^{11} U.S. dollars or 489 billion U.S. dollars (\$489B) (Table 3). On an area-normalized basis for Entisols, the value of SIC per square meter is \$0.46 m^{-2} (Table 3) using eqn. (2). Note that the price values calculated in U.S. dollars and dollars per square meter represent the money that would be required to purchase agricultural limestone to match the naturally-occurring SIC levels.

For the Cornell University Willsboro Research Farm, the mean total SIC storage and content data were acquired from fifty-four cores collected in the summer of 1995 (depth ranges: 30-92 cm) and also from the SSURGO soil database (depth ranges: 183-236 cm). The Cornell University Willsboro Research farm is located in Willsboro, NY (44° 22' N, 73° 26' W) in northeastern part of New York State and has highly variable soils due to glacial deposits (Mikhailova et al., 2016). The three soil orders present at Willsboro Research Farm are Entisols, Inceptisols and Alfisols. Mean SIC storage and content values reported by Mikhailova et al. (2016) for the three soil orders and for the various soil map units (SMUs) present on the farm were converted to U.S. dollars and dollars per square meter in Microsoft Excel using a procedure similar to that described above with eqns. (1) and (2). For the state of New York (NY), the average price of agricultural limestone in 2014 was reported to be \$10.88 per U.S. ton (USGS, 2016). Using Entisols again as an example, Mikhailova et al. (2016) reported an area of 378,691 m^2 (~ 0.38 km^2), a mean SIC storage of 3.40×10^6 kg (i.e., 3.40×10^9 g), and a mean SIC content of 8.98 kg m^{-2} for the Willsboro Farm based on readily-available values from the SURRGO database (SSURGO, 2015). Using these values together with the 2014 average

NY price of limestone in eqns. (1) and (2) results in values of $\$3.40\times10^{5}$ (\$0.34M) and $\$0.90\ m^{-2}$ (Table 4).

5. Results and Discussion

Soil inorganic carbon naturally occurring in the soil provides a substantial monetary value to the United States (Table 3). If the SIC is not naturally present in the soil, then liming is possibly needed to increase soil pH and nutrient availability; however, providing lime to the soil can be an expensive endeavor and can contribute to carbon emissions worldwide (West and McBride, 2005). Prices for agricultural limestone vary by state: for example, the average 2014 price of agriculture limestone was \$10.88 per U.S. ton in the state of New York and was \$10.42 per U.S. ton when averaged across the entire country (USGS, 2016). On the other hand, in certain states the price for agricultural limestone will be much higher (e.g., \$48.25 per U.S. ton in 2017 in the State of South Carolina, SC Department of Agriculture, 2017). The value of SIC varies by soil order, storage and content.

5.1. The value of SIC at country scale (2-m depth)

Total SIC storage represents the total amount of SIC in each soil order in 2 m depth shown as minimum (min), midpoint (mid), and maximum (max) (Table 3a). Including the min, mid and max values represents the inherent uncertainty in the STATSGO-derived estimates (Helmick et al, 2014). Helmick et al. (2014) found that the min and max values for a range of soil properties (e.g., organic carbon content, pH, and clay content) approximated 95% prediction intervals when compared with soil profile data. Previous research by Folberth et al. (2016) called for improvements in soil data and accounting for soil data uncertainty in crop yield simulations.

In this study the three soil orders with the highest SIC mid storage, Mollisols, Alfisols, and Aridisols, are categorized as intermediately weathered soil orders (Table 3a). Conversely, soils with lower SIC storage are categorized as slightly weathered and strongly weathered soil orders. Across the U.S., the soil orders having the highest total midpoint value of SIC storage (based on the average \$10.42 price of $CaCO_3$ per ton), are: 1) Mollisols (\$2.22T), 2) Aridisols (\$1.23T), 3) Alfisols (\$523B) and 4) Entisols (\$489B). The value of SIC in Mollisols and Alfisols is related to the midpoint SIC storage as reported by Guo et al. (2006). Both Mollisols and Alfisols are important agricultural soils for crop production and commonly located in the bread-basket regions (Liu et al., 2012). Predominant land use is grain production (maize, soybean, wheat, and sorghum) and livestock agriculture (Liu et al., 2012). The soil order Aridisols is ranked second in terms of SIC storage value (Table 3a), but high contents of SIC and limited precipitation can further limit agricultural and other uses in these soils (Rasmussen, C., 2006; Eghbal and Southard, 1993; Bockheim and Hartemink, 2013). Slightly weathered Entisols have the fourth highest SIC storage value of the 12 soil orders in the United States.

Soil inorganic carbon mid content (per square meter) represents the area density of SIC within the total area that each soil order occupies in the United States (Table 3b). In terms of SIC mid content results, the soil orders are ranked: 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}). Vertisols are ranked highest in terms of SIC content value since Vertisols have the highest density of SIC within the amount of occupied area.

5.2. The value of SIC storage at farm scale

The mean total SIC storage at the Cornell University Willsboro Research Farm was acquired from SSURGO data (Table 4), averaged soil core results (Table 5), and interpolated soil core results (Table 6). For the Cornell University Willsboro Research Farm, the soil orders having the highest total value of SIC (based on the average $10.88 price per U.S. ton of CaCO3 lime in NY in 2014), are: 1) Alfisols, 2) Entisols and 3) Inceptisols, which is somewhat consistent with results found at the country scale. The mean total SIC content followed similar rankings by soil order. At farm-scale, SSURGO data did not align with field data acquired from averaged and interpolated soil cores due to various reasons (e.g. soil depth, carbon data from "type location," etc.) (Mikhailova et al., 2016).

6. Conclusions

This study examined SIC storage and content at country scale (the continental U.S.) and farm scale (Cornell University Willsboro Research Farm) by calculating the corresponding monetary value of occurring SIC. The value of SIC is correlated with the sizes of SIC stocks, which tend to be highest in the Central Midwest-Great Plains and arid regions. Based on the results, it can be concluded that the value of SIC storage and content varies within the continental U.S at the country scale and also between specific data sources (SSURGO, averaged core results, and interpolated core results) at the farm scale. Calculating the value of SIC pools is important in ecosystem services assessment, especially provisioning and supporting services.

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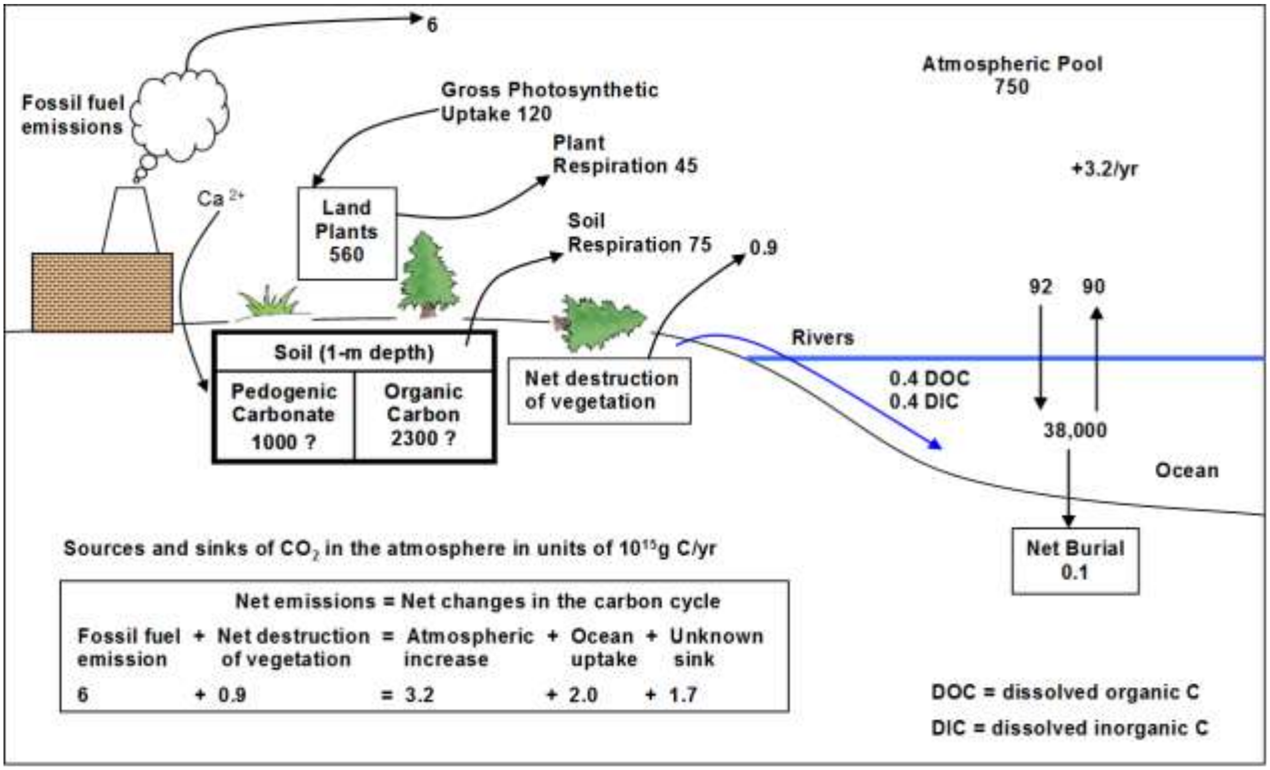

6
Fossil fuel emissions
Gross Photosynthetic Uptake 120
Atmospheric Pool 750
Plant Respiration 45
+3.2/yr
Ca^{2+}
Land Plants 560
Soil Respiration 75
0.9
92
90
Rivers
Soil (1-m depth)
Pedogenic Carbonate 1000 ?
Organic Carbon 2300 ?
Net destruction of vegetation
0.4 DOC
0.4 DIC
38,000
Ocean
Net Burial 0.1
Sources and sinks of CO_2 in the atmosphere in units of 10^{15}g C/yr
Net emissions = Net changes in the carbon cycle
Fossil fuel emission + Net destruction of vegetation = Atmospheric increase + Ocean uptake + Unknown sink
6 + 0.9 = 3.2 + 2.0 + 1.7
DOC = dissolved organic C
DIC = dissolved inorganic C

Fig. 1.

Table 1

Types of soil carbon and their importance to the ecosystem services listed by Adhikari and Hartemink (2016).

Ecosystem services	Soil organic carbon (SOC)	Soil inorganic carbon (SIC)	Total carbon (TC)
Provisioning services:			
- Food, fuel, and fiber	x	x	x
- Raw materials	x	x	x
- Gene pool			
- Fresh water /water retention	x	x	x
Regulating services:			
- Climate and gas regulation	x	x	x
- Water regulation	x	x	x
- Erosion and flood control	x	x	x
- Pollination/seed dispersal			
- Pest and disease regulation	x	x	x
- Carbon sequestration	x	x	x
- Water purification		x	x
Cultural services:			
- Recreation/ecotourism	x	x	x
- Esthetic/sense of place	x	x	x
- Knowledge/education/inspiration		x	x
- Cultural heritage			
Supporting services:			
- Weathering/soil formation	x	x	x
- Nutrient cycling	x	x	x
- Provisioning of habitat	x	x	x

Table 2
Examples of SIC and its importance for the ecosystem services listed by Adhikari and Hartemink (2016).

Ecosystem services	Soil inorganic carbon (SIC)	Example(s)	Citations
Provisioning services:			
- Food, fuel, and fiber	x	Regulation of soil pH	Mikhailova et al., 2006
- Raw materials	x	Natural liming material	West and McBride, 2005
- Gene pool			
- Fresh water/water retention	x	Liming improves water infiltration for acidic soils	USDA/NRCS, 1999
Regulating services:			
- Climate and gas regulation	x	Pedogenic carbonates	Zamanian et al., 2016
- Water regulation	x	Buffers lake acidity	Berner and Berner, 1996
- Erosion and flood control	x	Sinkholes (erosion)	Salvati and Sasowsky, 2002
- Pollination/seed dispersal			
- Pest and disease regulation	x	Alkalinity may reduce bacteria in soils	Berner and Berner, 1996
- Carbon sequestration	x	Pedogenic carbonates	Monger et al., 2015
- Water purification	x	Alkalization	Berner and Berner, 1996
Cultural services:			
- Recreation/ecotourism	x	Caliché, desert pavements	Schlesinger, 1982
- Esthetic/sense of place	x	Soil color (gray, white)	Arizona-Sonora Desert Museum, 2017
- Knowledge/education/inspiration	x	Desert museum	Arizona-Sonora Desert Museum, 2017
- Cultural heritage			
Supporting services:			
- Weathering/soil formation	x	Pedogenic carbonates	Zamamian et al., 2016
- Nutrient cycling	x	Source of Ca^{2+}, Mg^{2+}, etc.	Lal et al., 2000
- Provisioning of habitat	x	Tunnels, burrows	Canti et al., 2015

Table 3a
Soil orders with SIC storage in the upper 2 m and rankings for the conterminous United States.

No.	Name (Typical profile)	Description	Total area of soil order (Guo et al., 2006)	Total SIC storage (Guo et al., 2006)			Value of total SIC storage based on $10.42 price per U.S. ton of $CaCO_3$ lime in U.S. (2014)		
				Min	Mid	Max	Min	Mid	Max
			---------- km^2 ------	----------------- 10^6 Mg ---------------			--------------------------- $ -------------------------------------		
Slight weathering									
1.	Entisols A, C	Embryonic soils with ochric epipedon.	1.1×10^6 (3)	1995 (3)	5112 (4)	8901 (4)	1.91E+11 (3)	4.89E+11 (4)	8.52E+11 (4)
2.	Inceptisols A, Bw, C	Young soils with ochric or umbric epipedon (B horizon).	7.9×10^5 (6)	1956 (4)	4006 (5)	6612 (5)	1.87E+11 (4)	3.83E+11 (5)	6.33E+11 (5)
3.	Histosols O1, O2, O3, C	Organic soils with >20% of organic matter.	1.1×10^5 (9)	63 (7)	260 (7)	534 (7)	6.03E+9 (7)	2.49E+10 (7)	5.11E+10 (7)
4.	Gelisols A, Cf	Frozen soils with permafrost.	-	-	-	-	-	-	-
5.	Andisols A, B	Volcanic soils.	6.9×10^4 (10)	1 (9)	2 (9)	3 (9)	9.57E+7 (9)	1.91E+8 (9)	2.87E+8 (9)
Intermediate weathering									
6.	Aridisols A, Bt, Ck (or Ckm, Cy, Cz)	Dry soils. Common in the desert areas.	8.1×10^5 (5)	5630 (2)	12890 (2)	22135 (2)	5.39E+11 (2)	1.23E+12 (2)	2.12E+12 (2)
7.	Vertisols A, Bss (or Bssk), C	High in swelling clays, deep cracks when soil is dry.	1.3×10^5 (8)	1360 (6)	3075 (6)	5072 (6)	1.30E+11 (6)	2.94E+11 (6)	4.85E+11 (6)
8.	Alfisols A, E, Bt, C	Argillic, nitric, or kandic horizon; medium base saturation.	1.3×10^6 (2)	1649 (5)	5461 (3)	10296 (3)	1.58E+11 (5)	5.23E+11 (3)	9.86E+11 (3)
9.	Mollisols A, Bt (or Bw), C	Mollic epipedon, high base saturation, fertile soils.	2.0×10^6 (1)	9908 (1)	23181 (1)	39894 (1)	9.48E+11 (1)	2.22E+12 (1)	3.82E+12 (1)
Strong weathering									

10.	Spodosols A, E, Bs (or Bhs), C	Spodic horizon with Fe, Al oxides and humus accumulation.	2.5×10^5 (7)	50 (8)	149 (8)	282 (8)	4.79E+9 (8)	1.43E+10 (8)	2.70E+10 (8)
11.	Ultisols A, E, Bt, C	Argillic or kandic horizon, low base saturation.	8.6×10^5 (4)	0 (10)	0 (10)	0 (10)	0 (10)	0 (10)	0 (10)
12.	Oxisols A, Bo (or Bv), C	Oxic horizon, no argillic horizon, highly weathered.	-	-	-	-	-	-	-
	Totals		7.4×10^6	22612	54136	93729	2.16E+12	5.17E+12	8.97E+12

Table 3b
Soil orders with SIC content in the upper 2 m and rankings for the conterminous United States.

No.	Name (Typical profile)	Total SIC content (Guo et al., 2006)			Value of total SIC content based on \$10.42 price per U.S. ton of $CaCO_3$ lime in U.S. (2014)		
		Min	Mid	Max	Min	Mid	Max
		---------- kg C m^{-2} ----------			---------- \$ m^{-2} ----------		
Slight weathering							
1.	Entisols A, C	1.9 (5)	4.8 (5)	8.4 (5)	0.18 (5)	0.46 (5)	0.80 (5)
2.	Inceptisols A, Bw, C	2.5 (4)	5.1 (4)	8.4 (4)	0.24 (4)	0.49 (4)	0.80 (4)
3.	Histosols O1, O2, O3, C	0.6 (7)	2.4 (7)	5.0 (7)	0.06 (7)	0.23 (7)	0.48 (7)
4.	Gelisols A, Cf	-	-	-	-	-	-
5.	Andisols A, B	0.0 (9)	0.0 (9)	0.0 (9)	0.00 (9)	0.00 (9)	0.00 (9)
Intermediate weathering							
6.	Aridisols A, Bt, Ck (or Ckm, Cy, Cz)	7.0 (2)	15.9 (2)	27.3 (2)	0.67 (2)	1.52 (2)	2.61 (2)
7.	Vertisols A, Bss (or Bssk), C	10.3 (1)	23.2 (1)	38.3 (1)	0.99 (1)	2.22 (1)	3.67 (1)
8.	Alfisols A, E, Bt, C	1.3 (6)	4.3 (6)	8.1 (6)	0.12 (6)	0.41 (6)	0.78 (6)
9.	Mollisols A, Bt (or Bw), C	4.9 (3)	11.5 (3)	19.7 (3)	0.47 (3)	1.10 (3)	1.89 (3)
Strong weathering							
10.	Spodosols A, E, Bs (or Bhs), C	0.2 (8)	0.6 (8)	1.1 (8)	0.02 (8)	0.06 (8)	0.11 (8)

11.	Ultisols A, E, Bt, C	0.0 (10)	0.0 (10)	0.0 (10)	0.00 (10)	0.00 (10)	0.00 (10)
12.	Oxisols A, Bo (or Bv), C	-	-	-		-	

Table 4

Value of SIC inventory by soil type and soil order based on information reported in the SSURGO (2015) database for the Cornell Willsboro Research Farm (modified from Mikhailova et al., 2016).

Soil order / Soil series (Map unit symbol, MSU)	Total area	Total reported depth	Total mean SIC content	Value of total mean SIC content based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)	Total mean SIC storage	Value of total mean SIC storage based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)
	m^2	cm	kg C m^{-2}	$ m^{-2}	kg C	$
Alfisols (total)	**937940**	**201 ± 27***	**25.75**	**2.57**	**2.41×10^7**	**2.41×10^6**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	183	21.50	2.15	5.82×10^6	5.82×10^5
Churchville loam, 2 to 8 percent slopes (CpB)	36900	183	32.38	3.23	1.19×10^6	1.19×10^5
Covington clay, 0 to 3 percent slopes (CvA)	49076	183	16.25	1.62	7.97×10^5	7.97×10^4
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	183	10.64	1.06	6.24×10^5	6.24×10^4

Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	236	30.06	3.00	1.44×10^{7}	1.44×10^{6}
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	236	30.06	3.00	1.26×10^{6}	1.26×10^{5}
Entisols (total)	**378691**	**183 ± 0**	**8.98**	**0.90**	$\mathbf{3.40\times10^{6}}$	$\mathbf{3.40\times10^{5}}$
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	183	15.71	1.57	1.01×10^{6}	1.01×10^{5}
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	183	14.19	1.42	2.39×10^{6}	2.39×10^{5}
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	183	0.00	0.00	0.00	0.00
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	183	0.00	0.00	0.00	0.00
Inceptisols (total)	**157764**	**183 ± 0**	**23.17**	**2.32**	$\mathbf{3.65\times10^{6}}$	$\mathbf{3.65\times10^{5}}$
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	183	29.78	2.98	9.48×10^{4}	9.48×10^{3}

Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	183	29.88	2.99	2.53×10^{5}	2.53×10^{4}
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	183	22.63	2.26	8.83×10^{5}	8.83×10^{4}
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	183	22.63	2.26	2.42×10^{6}	2.42×10^{5}
Total value						**3.11×10^{6}**

[*] Means ± standard deviations for the reported depths in the soil order.

Table 5

Values of SIC inventory by soil type and soil order from averaged soil core results at the Cornell Willsboro Research Farm (original data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol, MSU)	Total area	Number of cores	Core depth	Total mean SIC content	Value of total mean SIC content based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)	Total Mean SIC Storage	Value of total mean SIC storage based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)
	m^2		cm	kg C m^{-2}	\$ m^{-2}	kg C	\$
Alfisols (total)	**937940**	**32**	**84 ± 29***	**2.92****	**0.29**	**2.74×10^6**	**2.74×10^5**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	10	68 ± 37	2.50 ± 4.22	0.25 ± 0.42	6.76×10^5	6.76×10^4
Churchville loam, 2 to 8 percent slopes (CpB)	36900	n/a***	n/a	n/a	n/a	n/a	n/a
Covington clay, 0 to 3 percent slopes (CvA)	49076	1	92	0.00	0.00	0.00	0.00
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	n/a	n/a	n/a	n/a	n/a	n/a
Kingsbury silty clay	480679	19	94 ± 19	3.62 ± 4.41	0.36 ± 0.44	1.74×10^6	1.74×10^5

loam, 0 to 3 percent slopes (KyA)							
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	2	115 ± 5	0.96 ± 1.35	0.10 ± 0.13	4.01×10^4	4.01×10^3
<u>Entisols (total)</u>	**378691**	**18**	**84 ± 21**	**1.65**	**0.16**	$\mathbf{6.25\times10^5}$	$\mathbf{6.25\times14^5}$
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	4	84 ± 20	0.31 ± 0.62	0.03 ± 0.06	1.99×10^4	1.99×10^3
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	6	83 ± 31	3.50 ± 5.41	0.35 ± 0.54	5.90×10^5	5.90×10^4
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	1	91	0.00	0.00	0.00	0.00
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	7	85 ± 15	0.11 ± 0.26	0.01 ± 0.03	1.56×10^4	1.56×10^3
<u>Inceptisols (total)</u>	**157764**	**4**	**63 ± 33**	**1.14****	**0.11**	$\mathbf{1.80\times10^5}$	$\mathbf{1.80\times10^4}$
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	n/a	n/a	n/a	n/a	n/a	n/a

Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	n/a	n/a	n/a	n/a	n/a	n/a
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	3	74 ± 31	4.28 ± 7.42	0.43 ± 0.74	1.67×10^5	1.67×10^4
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	1	30	0.00	0.00	0.00	0.00
Total value							**3.54×10^5**

* Means ± standard deviations, unless only one soil core was taken from a specific SMU.
** Reported value omits areas of SMUs from which no soil cores were taken.
*** n/a: not applicable. No soil core was taken from the specific SMU.

Table 6

Value of SIC inventory by soil type and soil order from interpolated soil core results at the Cornell Willsboro Research Farm (original data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol, MSU)	Total area	Total mean SIC content	Value of total mean SIC content based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)	Total mean SIC storage	Value of total mean SIC storage based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)
	m^2	kg C m^{-2}	\$ m^{-2}	kg C m^{-2}	$
<u>Alfisols (total)</u>	**937940**	**2.85**	**0.28**	$\mathbf{2.67\times10^6}$	$\mathbf{2.67\times10^5}$
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	2.48	0.25	6.71×10^5	6.71×10^4
Churchville loam, 2 to 8 percent slopes (CpB)	36900	4.29	0.43	1.58×10^5	1.58×10^4
Covington clay, 0 to 3 percent slopes (CvA)	49076	4.72	0.47	2.32×10^5	2.32×10^4
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	0.79	0.08	4.64×10^3	4.64×10^2

Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	3.13	0.31	1.50×10^{6}	1.50×10^{5}
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	1.38	0.14	5.79×10^{4}	5.79×10^{3}
Entisols (total)	**378691**	**1.31**	**0.13**	$\mathbf{4.95\times10^{5}}$	$\mathbf{4.95\times10^{4}}$
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	0.78	0.08	5.01×10^{4}	5.01×10^{3}
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	2.38	0.24	4.01×10^{5}	4.01×10^{4}
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	0.08	0.01	2.65×10^{1}	2.65×10^{0}
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	0.30	0.03	4.37×10^{4}	4.37×10^{3}
Inceptisols (total)	**157764**	**2.70**	**0.27**	$\mathbf{4.26\times10^{5}}$	$\mathbf{4.26\times10^{4}}$
Amenia fine sandy	3185	4.62	0.46	1.47×10^{4}	1.47×10^{3}

loam, 2 to 8 percent slopes (AmB)					
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	1.41	0.14	1.20×10^{4}	1.20×10^{3}
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	4.54	0.45	1.77×10^{5}	1.77×10^{4}
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	2.07	0.21	2.22×10^{5}	2.22×10^{4}
Total					**3.59×10^{5}**