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Accounting for Soil Inorganic Carbon in the Ecosystem Services Framework for United Nations Sustainable Development Goals

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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 soil ecosystem services framework should not include only soil organic carbon (SOC), but SIC as well since it is of global importance to soil fertility and the long-term carbon cycle, especially in semiarid and arid climates where SIC comprises the largest carbon pool. The objective of this study is to assess the value of SIC in the 12 soil orders of Soil Taxonomy within the continental United States (U.S.) and at the farm scale (the Cornell University Research Farm) within the context of ecosystem services, specifically provisional and supporting services. At the country scale, the total value of SIC storage is \$5.17E+12 (upper 2-m soil depth). The soil orders having the highest total value of SIC storage (based on \$10.42 price per U.S. ton of $CaCO_3$ lime in the U.S. (2014)) are: 1) Mollisols (\$2.22E+12), 2) Aridisols (\$1.23E+12), 3) Alfisols (\$5.23E+11), and 4) Entisols (\$4.89E+11). In terms of SIC content results (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 (variable soil depth), the soil orders having the highest total value of SIC (based on \$10.88 price per U.S. ton of $CaCO_3$ for the state of New York (NY) in 2014) are: 1) Alfisols, 2) Inceptisols, and 3) Entisols; however, the estimates were highly variable between

SSURGO and field-derived data. The results of this study provide an estimated value of soil inorganic carbon, which may be useful in assessing ecosystem services provided by the SIC. 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 time scales, as well as the potential need of including total carbon (TC) and interactions between SIC and SOC pools.

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

DEDICATION

I am dedicating this thesis to my family and friends who have motivated and inspired me to become a passionate, lifelong learner.

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CHAPTER ONE

PREFACE

This research explores accounting for soil inorganic carbon (SIC) in the ecosystem services framework for United Nations (UN) Sustainable Development Goals. Ecosystem services are defined as the benefits that are provided from the ecosystem to people (Millennium Ecosystem Assessment, 2005). Ecosystem services are divided into four broad categories: provisioning services, regulating services, cultural services, and supporting services (Holzman, 2012). The motivation behind this research is to demonstrate the importance of adding soil inorganic carbon's contribution to the key list of soil properties related to ecosystem services.

Soil inorganic carbon is a critical component of the global carbon budget, global carbon cycle, and comprises the largest terrestrial carbon pool (Monger et al., 2015). Soil inorganic carbon is not listed in ecosystem services, despite its importance in soil classification, taxonomy, fertility, and ample economic value. Soil inorganic carbon can be found in varying forms within the soil profile such as gaseous carbon dioxide, ionically as bicarbonate or carbonate ions, carbonic acid, or precipitated forms such as carbonate minerals, which is the focus of my research (Zamanian et al., 2016). Soil inorganic carbon has a close relationship with soil pH. For example, when the soil pH is alkaline, inorganic carbon forms are more susceptible to precipitate; however, when soil pH is acidic, inorganic carbon forms are more likely to be present within the soil profile ionically or as carbonic acid (Zamanian et al., 2016). In agriculture, inorganic carbon is commonly used as a liming material to raise the soil pH in acidic soils (Halvin et al., 2013). If an agricultural field is within an optimal pH range, inorganic carbon is applied to buffer against a future change in soil pH from sources such as acid rain (Halvin et al., 2013).

There are two main forms/origins of carbonates in soils: lithogenic and pedogenic. Lithogenic carbonates are rock-forming carbonates (e.g., limestone or dolomite). They are found as bulk deposits in marine environments such as a shallow sea (Monger et al., 2015). Due to their bulk deposition, lithogenic carbonates are economically feasible to extract or mine as a raw material for use as a commodity. On the contrary, pedogenic carbonates are formed within the soil (authigenically) and not economically feasible to extract, but can provide the same benefits as lithogenic carbonates (e.g.,, as naturally present liming material) (Monger et al., 2015).

Soil inorganic carbon has two main pathways of precipitation, which is important for regulating services, specifically climate regulation and carbon sequestration services. The first pathway can sequester atmospheric carbon if the calcium ion is sourced from siliceous parent material (Lal, 2016). The second pathway is the re-precipitation of a formerly dissolved carbonate; however, this pathway does not sequester atmospheric carbon (Monget et al., 2015). In addition, if re-precipitation does not occur, the dissolution of a preexisting carbonate can be an ecosystem disservice by becoming a source of atmospheric carbon (Zamanian et al., 2016).

Soil quality and soil health are critical for meeting the United Nations Sustainable Development Goals such as mitigating poverty, ending hunger, and developing prosperity for all (Lal, 2016). Soil quality and soil health are terms commonly used interchangeably to describe the soil's competency to function as a system; however, soil quality and soil health have exclusive definitions (Laishram et al., 2012). Soil quality is the ability of a soil to function within an ecosystem (natural or managed) boundaries, to support plant and animal productivity, human health, and habitation as well as maintaining or enhancing air and water quality (Karlen et al. 1997, Arshad and Martin, 2002). Soil health encompasses the same definition as soil quality; however, soil health focuses primarily on the biological and ecological components within the soil such as diseases suppressive attributes (Lal, 2016). The definition of soil health varies among sources; therefore, a distinct definition of soil health is unclear. Soil quality and soil health describe properties of the soil, while ecosystem services describe the soil properties as either benefits (services) or detriments (disservices) to humans. Ecosystem services can be used as an economic analysis of environmental issues; therefore, use of the ecosystem services framework is an improved approach for ecosystem evaluation than the independent use of either soil quality or soil health (Appendix A: Preface Table 1P).

Soil inorganic carbon is not accounted for in the list of key soil properties related to ecosystem services; however, SIC is prominent in all four broad categories of ecosystem services, and therefore should be included in the ecosystem services framework.

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CHAPTER TWO

Accounting for soil inorganic carbon in the ecosystem services framework for United Nations Sustainable Development Goals

Introduction

Soil inorganic carbon (SIC) is a part of total carbon (TC) in soils, however, it is currently not included in the list of key soil properties related to ecosystem services (e.g., provisioning, regulating, cultural, and supporting services) (Appendix B: 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 UN Sustainable Development Goals because soils help 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, & fiber, raw materials, gene pool, fresh water / water retention), 2. regulating services (climate & gas regulation, water regulation, erosion & flood control, pollination / seed dispersal, pest & 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 & Hartemink, 2016). The ecosystem services that relate to soil properties of total carbon include provisioning services: food, fuel, & fiber, raw materials, and fresh water / water retention; regulating services: climate & gas regulation, water regulation, erosion & flood control, pest & 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 & 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 ecosystems framework; however, SIC is not included, despite the contribution of SIC to the ecosystem services framework. 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, alone comprise a larger terrestrial carbon pool than SOC (Monger et al., 2015). Furthermore, solid-phase 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 commonly under 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 within the 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.

1. Soil inorganic carbon and Soil Taxonomy

Soil inorganic carbon has variable distribution in the United States by soil order and depth. Guo et al. (2006) reported half of 12 soil orders having significant accumulations of SIC, and ranked the soil orders by midpoint SIC storage in the following order: Mollisols (1), Aridisols (2), Alfisols (3), Entisols (4), Inceptisols (5), Vertisols (6). (Appendix A: Table 1). Soils with “slight” and “intermediate” degrees of weathering tend to have more carbonates (Appendix A: Table 1). Soils with a “strong” degree of weathering have little to no SIC accumulations (Appendix A: Table 1). Mollisols (1), Alfisols (2), and Vertisols (6) are globally important soil orders 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 letters symbolize characteristics within the master horizons (e.g., k = accumulation of carbonates, c = carbonate concretions or nodules, etc.) (Appendix A: Table 1) (Soil Survey Staff, 2014). The spatial and vertical distribution of SIC is influenced by rainfall amounts, which tend to decrease from east to west in the U.S. Therefore, more carbonate-rich soils are found in the western part of the country. Because agricultural activity is influenced by soil pH and naturally available SIC (liming material), the early agricultural exploration was somewhat driven from east coast to the west by the search of naturally neutral and fertile soils (Richter et al., 2001).

2. Soil inorganic carbon and ecosystem services

2.1. 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 etc.) and is important in food, fuel, and fiber production (Appendix A: Table 3) due to its influence on the soil pH (regulation of nutrient availability) (West and Bride, 2005; Mikhailova et al., 2006; Schaffner et al., 2012). It 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).

2.2. 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 due to the gas exchange between terrestrial $CaCO_3$ (pedogenic carbonate) and atmospheric CO_2 (Zamanian et al., 2016). Pedogenic carbonate can either sequester atmospheric carbon (service) during precipitation or release carbon to the atmosphere during dissolution (disservice) (Monger et al., 2015, Zamanian et al., 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). In addition, soil inorganic carbon can buffer acidity causing alkalization of the pedosphere and hydrosphere. Water with an acidic pH can have a significant impact on the quality; therefore, alkalization from soil inorganic carbon can naturally promote water purification (Berner and Berner, 1996).

2.3. 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 800×10^{15} 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).

2.4. 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, one source of calcium ions needed for carbonate precipitation are sourced from calcium containing igneous rocks that have weathered (Monger et al., 2015). 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 (Halvin et al., 2013). 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 U.S.) and 2) at the farm scale (Cornell University Willsboro Research Farm) within the context of ecosystem services, specifically provisioning and supporting services.

3. Materials and methods

For the continental U.S., initial data of midpoint SIC storage and content in 2-m soil depth were acquired from Guo et al. (2006), and converted to U.S. dollar values in Microsoft Excel. The U.S. dollar values were first calculated by multiplying the initial carbon estimate by the percent of carbon in $CaCO_3$ (12%), resulting in the total mass of $CaCO_3$ (in megagrams for SIC storage and kilograms for SIC content) needed to match the amount of inorganic carbon present in the soil. The $CaCO_3$ mass is then multiplied by 1.10231 to convert from megagrams (SIC storage) and 0.00110231 to convert from kilograms (SIC content), resulting in the amount of $CaCO_3$ needed in U.S. tons. At this point, the amount of carbon in $CaCO_3$ (in U.S. tons) matches the amount of inorganic carbon estimated in the soil. Next, the amount of $CaCO_3$ in U.S. tons is multiplied by the average price of agricultural limestone in the U.S., which, according to the U.S. Geological Survey (USGS), is $10.42 per U.S. ton (2014). The result is the U.S. dollar amount that represents the amount of money it would take to match the natural occurring SIC with agricultural limestone, $CaCO_3$.

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 from SSURGO soil database (depth ranges: 183-236 cm). The Cornell University Willsboro Research Farm is near Willsboro, New York (NY) (44° 22' N, 73° 26' W). There are three soil orders present at Willsboro Research farm: Entisols, Inceptisols, and Alfisols. Soil inorganic carbon data in each soil order on Willsboro Research Farm were converted to a U.S. dollar amount using the same methods, except the average price of agricultural limestone for NY was $10.88 per U.S. ton in 2014 (USGS, 2016). The price of agricultural limestone varies from state to state.

4. Results and Discussion

Soil inorganic carbon residing in the soil provides a substantial monetary value to the United States (Appendix A: 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 also can contribute to carbon emissions worldwide (West and McBride, 2005). Prices for agricultural limestone vary by state: for example, the average price of agriculture limestone is $10.88 per U.S. ton (2014) in the state of New York (USGS, 2016) and $48.25 per U.S. ton (2017) in the state of South Carolina (SC Department of Agriculture, 2017). The value of SIC varies by soil order, storage and content. 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 would be 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).

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

Midpoint SIC storage represents the total amount of SIC in each soil order (Appendix A: Table 3). The three soil orders with the highest SIC storage, Mollisols, Alfisols, and Aridisols, are categorized as intermediately weathered soil orders (Appendix A: Table 3). Conversely, soils with lower SIC storage are categorized as slightly weathered and strongly weathered soil orders. For the United States, the soil orders having the highest value of SIC storage (based on the national average $10.42 price of $CaCO_3$ per ton for the U.S. in 2014), are: 1) Mollisols ($2.22E+12), 2) Aridisols ($1.23E+12), 3) Alfisols ($5.23E+11), and 4) Entisols ($4.89E+11). 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 (Appendix A: Table 3), but high contents of SIC and limited precipitation can further limit agricultural and other uses in these soils due to formation of duripans (Rasmussen, C., 2006; Eghbal and Southard, 1993), and salinization (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 content (per square meter) represents the area density of SIC within the total area that each soil order occupies in the United States (Appendix A: Table 3). In terms of SIC 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 since Vertisols have the highest density of SIC within the amount of occupied area.

4.2. The value of SIC storage at farm scale

The mean total SIC storage at Cornell University Willsboro Research Farm was acquired from SSURGO data (Appendix A: Table 4), averaged soil core results (Appendix A: Table 5), and interpolated soil core results (Appendix A: Table 6). For the Cornell University Willsboro Research Farm, the soil orders having the highest total value of SIC storage (based on the average \$10.88 price per U.S. ton of $CaCO_3$ lime in NY in 2014), are: 1) Alfisols, 2) Entisols and 3) Inceptisols, which is considerably consistent with results found at the country scale. 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).

5. 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 Great Plains-Central Midwest 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.

CHAPTER THREE

SUMMARY

Research regarding soil inorganic carbon (SIC) as a key soil property to the ecosystem services framework and the overall assessment of SIC as a natural capital is at its infancy. The inclusion of SIC in the ecosystem services framework does not suggest the exclusion of soil organic carbon (SOC) in the framework; however, future research needs to consider the integration of SIC and SOC as total carbon (TC) within the ecosystem services framework. For example, the use of SIC and SOC collectively as TC will be dependent on the research conducted and may or may not be the best approach.

SSURGO (Soil Survey Geographic Database) and STATSGO (State Soils Geographic Database) are the two widely used soil databases in the United States with different scales of detail, 1:12,000–1:63,360 and 1:250,000, respectively (Gowda et al., 2013). Due to scale, the SSURGO database is more detailed, while the STATSGO database is generalized in comparison; therefore, SSURGO data is frequently used in research. However, my research revealed discrepancies in SIC estimates between acquired field data (averaged core results and interpolated core results) at farm scale and the spatially corresponding SSURGO data. Mikhailova et al. (2016) also found disparities between field measurements and the SSURGO database. There is a possibility the high variation between acquired field data and the SSURGO database is due to sources of error. For instance, SIC precipitates are depth-dependent; however, samples acquired from field data and SSURGO data were possibly collected at contrasting depths. Future research can address the problem of varying sample depths by only accounting for the top 0-12 inches, which is the most agriculturally important depth for crop growth and

SIC's contributing benefits. More research needs to be conducted on comparing values between acquired field data and the SSURGO database.

This research assigned a U.S. dollar value on SIC estimates at the country scale, within the continental United States and at the farm scale, at the Cornell University Willsboro Research Farm. The resulting monetary values for SIC storage and content in the continental United States are not exact evaluations for various reasons. For example, these research calculations utilized midpoint values for SIC storage and content in each soil order sourced from Guo et al. (2006). Also, Guo et al. (2006) SIC storage and content estimates were originally derived from the STATSGO database, which may have reported imprecise SIC storage and content estimates. Furthermore, the SIC value calculations for the continental United States were based on a national average of $10.42 price per U.S. ton of $CaCO_3$ lime in 2014 (USGS, 2016); however, the price per U.S. ton of $CaCO_3$ is highly variable among states. Future research can address this inaccuracy by applying monetary values for SIC storage and content based on state-specific prices of $CaCO_3$ per U.S. ton.

The precipitation of calcium carbonate ($CaCO_3$) is dependent on the chemical bonding between inorganic carbon forms ($CO_{2(g)}$, $CO_{2(aq)}$, H_2CO_3, HCO_3^-, and CO_3^{2-}) and calcium cations (Ca^{2+}) (Zamanian et al., 2016). Future research can use quantified estimates of Ca^{2+} annual atmospheric wet deposition and apply a corresponding annual monetary value. Also, dolomite ($CaMg(CO_3)_2$ is another pedogenic carbonate mineral that can be precipitated within the soil profile (Kearsey et al., 2012). The magnesium ions (Mg^{2+}) associated with dolomite precipitation can also be assigned a monetary value based on quantified estimates of annual atmospheric wet deposition. Further research applying a monetary value to SIC in varied respects such as the valuing the top 0-12 inches, state-to-state value, and ionic atmospheric deposition values can encourage an improved perspective on how the ecosystem services humans.

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APPENDICES

Appendix A

Tables

Table 1P. Relationship between soil quality, soil health, and ecosystem services (based on Arshad and Martin, 2002; Holzman, 2012; Lal, 2016; Karlen et al. 1997).

	Soil Quality	Soil Health	Ecosystem Services
Definition	Soil quality is the ability of a soil to function within an ecosystem (natural or managed) boundaries, to support plant and animal productivity, human health, and habitation as well as maintaining or enhancing air and water quality	Soil quality is the ability of a soil to function within an ecosystem (natural or managed) boundaries, to support plant and animal productivity, human health, and habitation as well as maintaining or enhancing air and water quality; however, soil health focuses more on the biology and ecology of the soil	Ecosystem services are defined as any positive benefit that is provided by the ecosystem to people.
Properties	Physical, chemical, biological, and ecological components.	Predominantly biological and ecological components.	Ecosystem services are divided into four broad categories: provisioning services, regulating services, cultural services, and supporting services
Applications	Assessment of physical, chemical, biological and ecological properties of the soil.	Strong focus on the assessment of biological and ecological properties of the soil.	Assessment of the services and disservices provided from the ecosystem to human beings. Can be used as an economic analysis of environmental issues.

Factors affecting Ecosystem Services	Physical: texture and surface area, structure, and erodibility, bulk density, porosity and pore size distribution, infiltration rate, AWC, depth. Chemical: pH, EC, CEC, nutrient reserves, heavy metals, elemental balance, carbonates. Biological: SOC, MBC, MRT and turnover, earthworms, soil enzymes, nematodes & pathogens, mycorrhizal fungi, respiration. Ecological: nutrient cycling, hydrological budget, energy budget, erosion, biodiversity, landscape processes.	Biological: SOC, MBC, MRT and turnover, earthworms, soil enzymes, nematodes and pathogens, mycorrhizal fungi, respiration. Ecological: nutrient cycling, hydrological budget, energy budget, erosion, biodiversity, landscape processes.

Abbreviations: Available water capacity (AWC), Cation-exchange capacity (CEC), Electrical conductivity (EC), Microbial biomass carbon (MBC), Mean residence time (MRT), Soil organic carbon (SOC)

Table 1

List of types of soil carbon related to ecosystem services as 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 ecosystem services as 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 3
Soil orders with SIC accumulations and rankings.

No.	Name (Typical profile)	Description	Total area of soil order (Guo et al., 2006)	Midpoint SIC storage (Guo et al., 2006)	Midpoint SIC content (Guo et al., 2006)	Value of midpoint total SIC storage based on $10.42 price per U.S. ton of $CaCO_3$ lime in U.S. (2014)	Content value of midpoint total SIC content based on $10.42 price per U.S. ton of $CaCO_3$ lime in U.S. (2014)
			---------- km^2 --------	--- 10^6 Mg C --	--- kg C m^{-2} ----	------------ $ ----------	--------- $ m^{-2} --------------
Slight weathering							
1.	Entisols A, C	Embryonic soils with ochric epipedon.	1.1×10^6 (3)	5112 (4)	4.8 (5)	4.89E+11 (4)	0.46 (5)
2.	Inceptisols A, Bw, C	Young soils with ochric or umbric epipedon (B horizon).	7.9×10^5 (6)	4006 (5)	5.1 (4)	3.83E+11 (5)	0.49 (4)
3.	Histosols O1, O2, O3, C	Organic soils with >20% of organic matter.	1.1×10^5 (9)	260 (7)	2.4 (7)	2.49E+10 (7)	0.23 (7)
4.	Gelisols A, Cf	Frozen soils with permafrost.	-	-	-	-	-
5.	Andisols A, B	Volcanic soils.	6.9×10^4 (10)	2 (9)	0.0 (9)	1.91E+8 (9)	0 (9)
Intermediate weathering							
6.	Aridisols A, Bt, Ck (or Ckm, Cy, Cz)	Dry soils. Common in the desert areas.	8.1×10^5 (5)	12890 (2)	15.9 (2)	1.23E+12 (2)	1.52 (2)
7.	Vertisols A, Bss (or Bssk), C	High in swelling clays, deep cracks when soil is dry.	1.3×10^5 (8)	3075 (6)	23.2 (1)	2.94E+11 (6)	2.22 (1)
8.	Alfisols A, E, Bt, C	Argillic, nitric, or kandic horizon; medium base saturation.	1.3×10^6 (2)	5461 (3)	4.3 (6)	5.23E+11 (3)	0.41 (6)
9.	Mollisols A, Bt (or Bw), C	Mollic epipedon, high base saturation, fertile soils.	2.0×10^6 (1)	23181 (1)	11.5 (3)	2.22E+12 (1)	1.10 (3)
Strong weathering							
10.	Spodosols A, E, Bs (or Bhs), C	Spodic horizon with Fe, Al oxides and humus accumulation.	2.5×10^5 (7)	149 (8)	0.6 (8)	1.43E+10 (8)	0.06 (8)

11.	Ultisols A, E, Bt, C	Argillic or kandic horizon, low base saturation.	8.6×10^5 (4)	0 (10)	0.0 (10)	0 (10)	0 (10)
12.	Oxisols A, Bo (or Bv), C	Oxic horizon, no argillic horizon, highly weathered.	-	-	-	-	-
	Totals		7.4×10^6	54136	7.4	5.17E+12	0.71

Table 4

Value of SIC inventory by soil type and soil order (SSURGO, 2015) from the SSURGO database at the Cornell Willsboro Research Farm (modified from Mikhailova et al., 2016).

Soil order / Soil series (Map unit symbol, MSU)	Total Area	Total Reported Depth	Mean SIC Content	Value of mean total SIC content based on $10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)	Mean SIC Storage	Value of mean total 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**	**2,408,620.84**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	183	21.50	2.15	5.82×10^6	581,666.94
Churchville loam, 2 to 8 percent slopes (CpB)	36900	183	32.38	3.23	1.19×10^6	118,931.90
Covington clay, 0 to 3 percent slopes (CvA)	49076	183	16.25	1.62	7.97×10^5	79,654.39
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	183	10.64	1.06	6.24×10^5	62,364.29

Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	236	30.06	3.00	1.44×10^7	1,439,175.94
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	236	30.06	3.00	1.26×10^6	125,927.89
Entisols (total)	**378691**	**183 $\pm$ 0**	**8.98**	**0.90**	$\mathbf{3.40 \times 10^6}$	**339,805.43**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	183	15.71	1.57	1.01×10^6	100,942.20
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	183	14.19	1.42	2.39×10^6	238,863.23
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 $\pm$ 0**	**23.17**	**2.32**	$\mathbf{3.65 \times 10^6}$	**364,791.12**
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	183	29.78	2.98	9.48×10^4	9,474.57

Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	183	29.88	2.99	2.53×10^5	25,285.52
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	183	22.63	2.26	8.83×10^5	88,249.47
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	183	22.63	2.26	2.42×10^6	241,861.51
Total value						**3,113,217.39**

* Means $\pm$ standard deviations for the reported depths in the soil order.

Table 5

Values of SIC inventory by soil type and soil order (SSURGO, 2015) 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	Mean SIC Content	Value of mean total SIC content based on \$10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)	Mean SIC Storage	Value of mean total 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	\$
<u>Alfisols (total)</u>	**937940**	**32**	**84 ± 29**[*]	**2.92**[**]	**0.29**	**2.74×10^6**	**273,843.20**
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	67,561.31
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
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	173,900.43

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}	4,007.71
<u>**Entisols (total)**</u>	**378691**	**18**	**84 ± 21**	**1.65**	**0.16**	$\mathbf{6.25\times10^{5}}$	**62,464.23**
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}	1,988.86
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}	58,966.24
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}	1,559.11
<u>**Inceptisols (total)**</u>	**157764**	**4**	**63 ± 33**	**1.14****	**0.11**	$\mathbf{1.80\times10^{5}}$	**17,989.70**
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}	16,690.44
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	1	30	0.00	0.00	0.00	0.00
Total value							**354,297.13**

[*] 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 (SSURGO, 2015) 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	Mean SIC Content	Value of mean total SIC content based on \$10.88 price per U.S. ton of $CaCO_3$ lime in NY (2014)	Mean SIC Storage	Value of mean total 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}	\$
Alfisols (total)	**937940**	**2.85**	**0.28**	**2.67×10^6**	**266,847.20**
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	2.48	0.25	6.71×10^5	67,061.60
Churchville loam, 2 to 8 percent slopes (CpB)	36900	4.29	0.43	1.58×10^5	15,790.96
Covington clay, 0 to 3 percent slopes (CvA)	49076	4.72	0.47	2.32×10^5	23,186.72
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	0.79	0.08	4.64×10^3	463.73

Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	3.13	0.31	1.50×10^{6}	149,914.16
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	1.38	0.14	5.79×10^{4}	5,786.69
Entisols (total)	**378691**	**1.31**	**0.13**	$\mathbf{4.95\times10^{5}}$	**49,471.67**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	0.78	0.08	5.01×10^{4}	5,007.13
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	2.38	0.24	4.01×10^{5}	40,077.05
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	0.08	0.01	2.65×10^{1}	2.65
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	0.30	0.03	4.37×10^{4}	4,367.50
Inceptisols (total)	**157764**	**2.70**	**0.27**	$\mathbf{4.26\times10^{5}}$	**42,575.62**
Amenia fine sandy	3185	4.62	0.46	1.47×10^{4}	1,469.16

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	1,199.31
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	4.54	0.45	1.77×10^5	17,689.87
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	2.07	0.21	2.22×10^5	22,187.30
Total					**358,894.49**

Appendix B

Figures

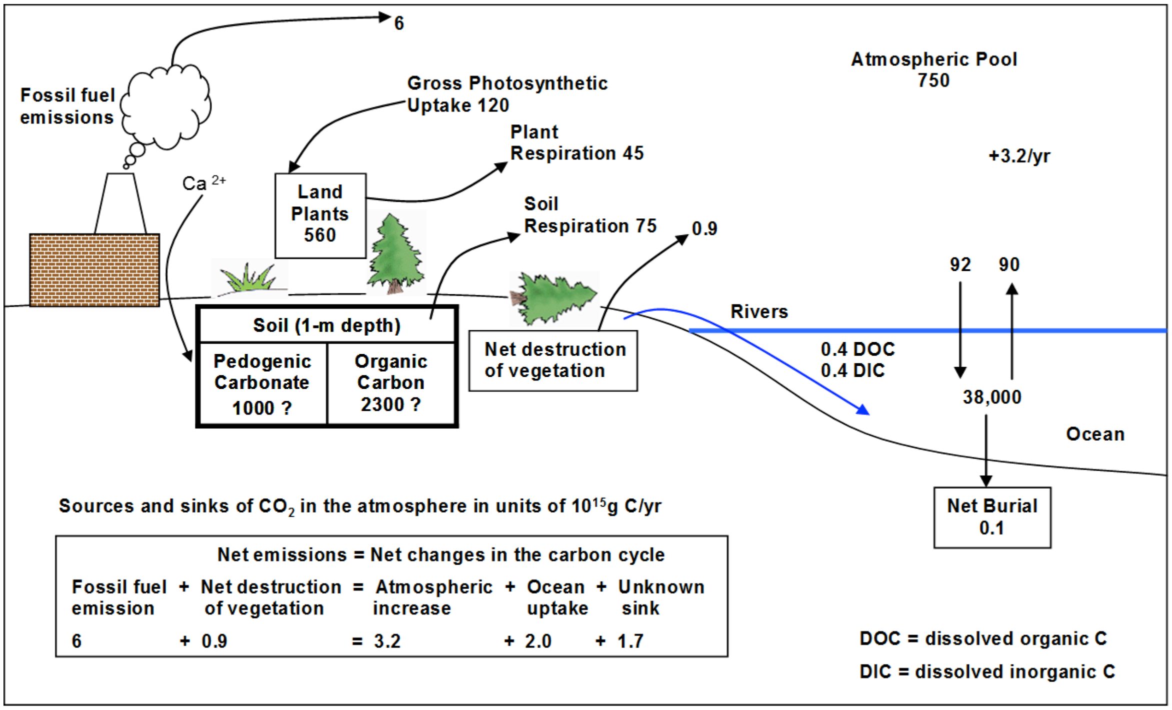
6
Atmospheric Pool
750
Fossil fuel emissions
Gross Photosynthetic Uptake 120
Plant Respiration 45
+3.2/yr
Ca 2+
Land Plants 560
Soil Respiration 75
0.9
92
90
Rivers
Soil (1-m depth)
Pedogenic Carbonate 1000 ?
Organic Carbon 2300 ?
Net destruction of vegetation
0.4 DOC
0.4 DIC
38,000
Ocean
Net Burial 0.1
Sources and sinks of CO2 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.

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