

Review

The Business Side of Ecosystem Services of Soil Systems

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Abstract: Current applications of the Ecosystems Services (ES) framework to soils are narrowly defined (e.g., soil-based, pedosphere-based, etc.), and focus on soil properties while treating soil as a closed system. Because soil is an open system, it receives and loses matter across its boundaries within Earth's spheres (atmosphere, biosphere, hydrosphere, lithosphere, ecosphere, and anthroposphere), which also need to be accounted for in economic analysis. In market economies, the market transforms resources from the Earth's pedosphere and related spheres into goods and services for societal welfare with non-market institutions mediating human and environmental interactions. These transformations and mediations can result not only in welfare but damages as well. The concept of soil ES and ecosystem disservices (ED) is a human-centered framework, which can be a useful tool in business decision-making. Soil ES (e.g., provisioning, regulation/ maintenance, and cultural) are used to produce goods and services, but the value of these ES and ED are not always accounted for as a part of business decision-making. The objective of this review is to illustrate the monetary valuation of ecosystem services of soil systems (SS) with examples based on the organizational hierarchy of soil systems. The organizational hierarchy of soil systems can be used in economic valuations of soil ES by scale (e.g., world, continent), time (e.g., soil, geologic), qualitative and quantitative degrees of computation (e.g., mental, verbal, descriptive, mathematical, deterministic, stochastic), and degree of complexity (e.g., mechanistic, empirical). Soil survey databases, soil analyses, Soil Data Systems (SDS), and Soil Business Systems (SBS) provide tools and a wide range of quantitative/qualitative data and information to evaluate goods and services for various business applications, but these sources of soil data may be limited in scope due to their static nature. Valuation of soil resources based on soil and non-soil science databases (e.g., National Atmospheric Deposition Program (NADP) databases, etc.) is critically needed to account for these ES/ED as part of business decision-making to provide more sustainable use of soil resources. Since most ecosystems on Earth have been modified by human activity, "soil systems goods and services" (SSGS) may be a more applicable term to describe soil contributions (benefits/damages) to economic activity, compared to a term such as "soil ecosystem goods and services."

Keywords: business ecosystems; information; intelligence; economics; market; pedosphere

1. Introduction

Ecological economics developed the concept of soil ecosystem services [1] (provisioning, regulation/ maintenance, and cultural), which provide goods and services for various business systems [2], but its

value often is not recognized due to the business community's unfamiliarity with the importance of soil [3]. For example, Watson and Newton (2018) [2] conducted a survey of business dependencies on various Ecosystems Services (ES) (including soil) in the English county of Dorset, and found that many businesses indicated little or no dependence on soil. Indeed, the value of soil ES is difficult to measure and report for the business community because of the complex nature of soil [4]. While some may question the need to monetize soil [4], others advocate the use of monetary valuation as a means to engage the business community "to achieve scalable solutions" to soil and environmental degradation [2,3]. The word "scalable" is key to understanding the complexity of soil, both with its definition as well as its ES. The current definition of soil is "the layer(s) of generally loose mineral and/or organic material that are affected by physical, chemical, and/or biological processes at/or near the planetary surface and usually hold liquids, gases, and biota and support plants" [5] (Figure 1a). This definition is inclusive of soils on planet Earth and other planets [5]. Traditionally, the definition of soil is applied to Earth, which implies "the multi-phase dimension of soil" as a product of interaction of the Earth's spheres (atmosphere, biosphere, hydrosphere, lithosphere) (Figure 1a). The pedosphere (from the Greek pedon = ground) is defined as "the soil mantle of the Earth" based on the "concept of soils as specific bodies in nature that developed in time and space in situ at the land surface due to processes resulting from interactions of soil-forming factors: parent material, climate, organisms, topography, and time" [6] (Figure 1b). According to Mattson, 1938 [7], not all soils form as a result of the interaction of the four of the Earth's spheres, and two-sphere, and three-sphere combinations are possible. For example, some organic soils are formed from Earth's three-sphere combinations (atmosphere, hydrosphere, and biosphere) (Figure 1b).

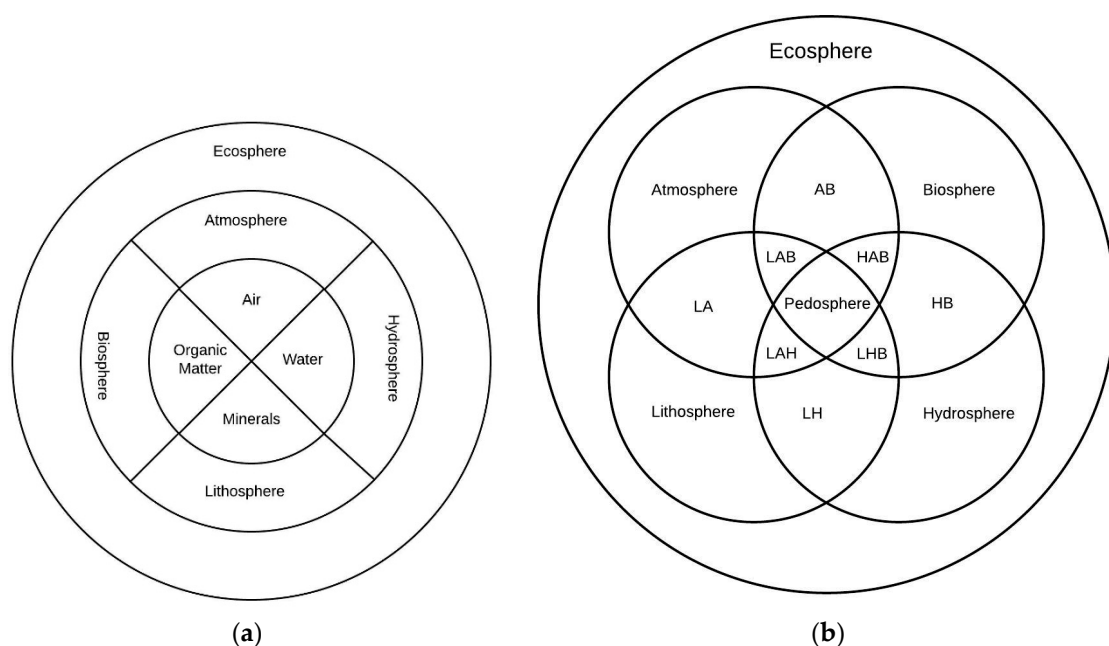


Figure 1. The scope of: (a) soil and relationship between soil components from various Earth's spheres; (b) formation of two-sphere, three-sphere, and four-sphere (e.g., pedosphere) systems in nature (A = atmosphere; B = biosphere; H = hydrosphere; L = lithosphere) (adapted from Mattson, 1938 [7]).

Humans use market and non-market tools to transform resources from the Earth's spheres into goods and services for societal welfare, with non-market institutions mediating human and environmental interactions [8] (Figure 2). These transformations and mediations result not only in welfare but damages as well, adding another of Earth's spheres—the anthroposphere ("realm of human society") [6].

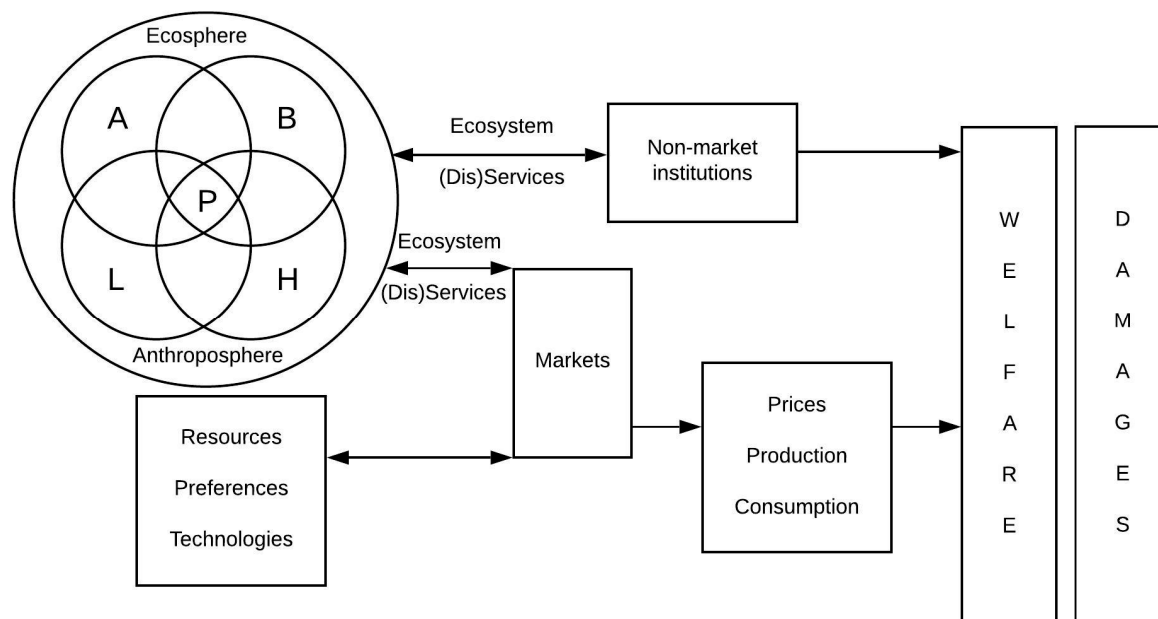


Figure 2. Conceptual diagram of how the market transforms resources from the Earth's spheres (A = atmosphere; B = biosphere; H = hydrosphere; L = lithosphere; P = pedosphere; Ecosphere, and Anthroposphere) into goods and services for societal welfare with non-market institutions mediating human and environmental interactions (adapted from Heal, 2000 [8]). These transformations and mediations can result not only in welfare but damages as well.

To understand the complex nature of soil, soil scientists have developed an organizational hierarchy of soil systems that is widely used for soil classification purposes [9,10]. Chandler et al. (2018) [11] proposed that frameworks for ES should be integrated with the organizational hierarchy of soil systems, which can be used for monetary valuation of soil ES by scale (e.g., world, continent), time (e.g., human, geologic), qualitative and quantitative degrees of computation (e.g., mental, verbal, descriptive, mathematical, deterministic, stochastic), and degree of complexity (e.g., mechanistic, empirical) (Table 1). According to Adhikari and Hartemink (2016) [12], soil scientists are reluctant to use the term “ecosystem services” [13] because many ecosystems on Earth have been modified by human activity. Therefore, soil systems goods and services (SSGS) may be a more acceptable term to describe soil benefits supplied to human societies compared to a term such as soil ecosystem goods and services (Table 1). The National Soil Survey Center (NSSC) provides a wide range of Soil Business Systems (SBS) tools to support the qualitative and quantitative assessment of soil systems business services. According to USDA/NRCS (2014) [14], SBS “application development includes, but is not limited to, NASIS (National Soils Database), Web Soil Survey, LIMS (Laboratory Management System), as well as 14 other soil applications and interfaces.” Soil survey databases and soil analyses provide a wide range of quantitative and qualitative data to evaluate SSGS for various business applications, but these sources of soil data may be limited in scope due to their static nature. Adhikari and Hartemink (2016) [12] provided a list of key soil properties related to ES, but this list is based on commonly used soil properties not originally intended for soil ES. Their list, therefore, may exclude important soil properties from ES valuations (e.g., calcium carbonates (%), which is a naturally present liming material in soils, soil organic matter (SOM), etc.) For example, soil inorganic carbon (SIC) and total soil carbon (TSC) currently are not included in Adhikari and Hartemink’s (2016) [12] list, but they do provide important ES [15–17]. Rawlins et al. [18] also documented the importance of inorganic carbon in soil carbon databases and stock estimates in England. The list of soil properties important for ES valuations may depend on individual/institutional preference (e.g., SOC versus SOM, etc.), and the availability of data in soil survey databases and field inventories.

Table 1. Integration of ecosystem services (ES) framework with organizational hierarchy of soil systems (adapted from Dijkerman, 1974 [9]; Hoosbeek and Bryant, 1992 [10]; Chandler et. al., 2018 [11]; Adhikari and Hartemink, 2016 [12]).

Organizational Hierarchy of Soil System				Framework for Ecosystem Services		
Soil System (Scale)	Time	Degree of ...		Ecosystem Services		
		Computation (Qualitative or Quantitative)	Complexity (Mechanistic or Empirical)	Provisioning	Regulation and Maintenance	Cultural
World i + 6	x	x	x	x	x	x
Continent i + 5	x	x	x	x	x	x
Region i + 4	x	x	x	x	x	x
Watershed i + 3	x	x	x	x	x	x
Catena i + 2	x	x	x	x	x	x
Polypedon i + 1	x	x	x	x	x	x
Pedon i	x	x	x	x	x	x
Soil horizon i – 1	x	x	x	x	x	x
Soil structure i – 2	x	x	x	x	x	-
Basic structure i – 3	x	x	x	x	x	-
Molecular interaction i – 4	x	x	x	x	x	-

Note: (i – 1) indicates the levels of scale hierarchy according to the organizational hierarchy of soil systems, where the behavior of a system at the extent scale (i level) can be described in terms of attributes at lower (–) or upper (+) scale levels (adapted from Dijkerman, 1974 [9]).

Because soil is an open system, it receives and loses matter across its boundaries within Earth's various spheres (atmosphere, biosphere, hydrosphere, lithosphere, ecosphere, and anthroposphere), which also need to be accounted for in business decision-making based on other databases (e.g., National Atmospheric Deposition Program (NADP) databases, etc.) The contribution of Earth's spheres to the pedosphere and SSGSs also can be valued using the organizational hierarchy of soil systems (Table 1). Most studies on soil ES overlook the fact that soil is a product of the interactions of Earth's spheres, which, therefore, make significant contributions to the pedosphere and SSGSs. Adhikari and Hartemink (2016) [12] stressed the importance of using holistic and interdisciplinary approaches to understanding soil ES. These approaches may require non-traditional methods of soil ES monetary valuations, which take into account the contribution of the Earth's spheres to the pedosphere and SSGSs. The objective of this review is to illustrate the valuation of SSGS (including the contribution of Earth's spheres to soil ES), with examples primarily from the U.S. based on the organizational hierarchy of soil systems, which may be applicable to other market economies.

2. Materials and Methods

2.1. Data Compilation

Examples of soil ES (including contribution of Earth's spheres to soil ES), and its monetary valuations were obtained from various literature sources using the Web of Science (Clarivate Analytics, 2020 [19]). These examples encompass the three major groups of ES commonly used in the literature: provisioning, regulation/maintenance, and cultural [20].

2.2. The Accounting Framework

Table 2 provides a conceptual overview of the accounting framework for the market and non-market valuation of benefits/damages from three groups of ES (provisioning, regulation/maintenance, and cultural) based on biophysical and administrative accounts with examples primarily from the U.S. and its soils, as well as the related market-based information obtained from U.S. sources.

Table 2. Conceptual overview of the accounting framework for a systems-based approach in the ecosystem services (ES) valuation of various soil systems goods and services (SSGS) based on organizational hierarchy of soil systems (adapted from Groshans et al., 2018 [15]).

Biophysical Accounts (Science-Based)	Administrative Accounts (Boundary-Based)	Monetary Accounts	Benefit/Damage	Total Value
Soil extent:	Administrative extent:	Ecosystem good(s) and service(s):	Sector:	Types of value:
Examples of monetary valuations based on soil properties and organizational hierarchy of soil systems				
Examples of monetary valuations based on interaction of pedosphere and Earth's other spheres and organizational hierarchy of soil systems				
Organizational hierarchy of soil system (i – 4 to i + 6)	Administrative organizational hierarchy (i – 4 to i + 6)	Provisioning, regulation/maintenance, and cultural	Environment, agriculture, industry etc.	Market and non-market valuations

Note: (i – 4) indicates the levels of scale hierarchy according to the organizational hierarchy of soil systems, where the behavior of a system at the extent scale (i level) can be described in terms of attributes at lower (–) or upper (+) scale levels (adapted from Dijkerman, 1974 [9]).

3. Results

3.1. Examples of Monetary Valuations Based on Soil Properties and Organizational Hierarchy of Soil Systems

3.1.1. Soil System (Scale)

According to Pachepsky and Hill (2017) [21], scale is used as a central concept in the hierarchical organizations of Earth's spheres (including the pedosphere), anthroposphere, and the world in general. Since soil ES is a human-centered framework, it requires the integration of soil systems and administrative scales used by humans. Figure 3 illustrates an example of using a soil systems scale at the farm to depict the regulating ES of total soil carbon (TSC) and its value based on an avoided social cost of carbon emission (SC-CO₂) of USD 42 per metric ton of CO₂, where soil map unit (SMU) and the soil order of Entisols represent science-based biophysical accounts within defined soil extent boundaries of the farm. Although useful for the science community, this type of valuation and presentation may not be applicable to the business community. Figure 4 illustrates the integration of soil systems and administrative scales, where a market-based valuation of a provisioning ES value (based on liming replacement cost) is used to demonstrate the soil inorganic carbon (SIC) replacement costs calculated from science-based accounts at the administrative scale: square meter, state, region, and country levels.

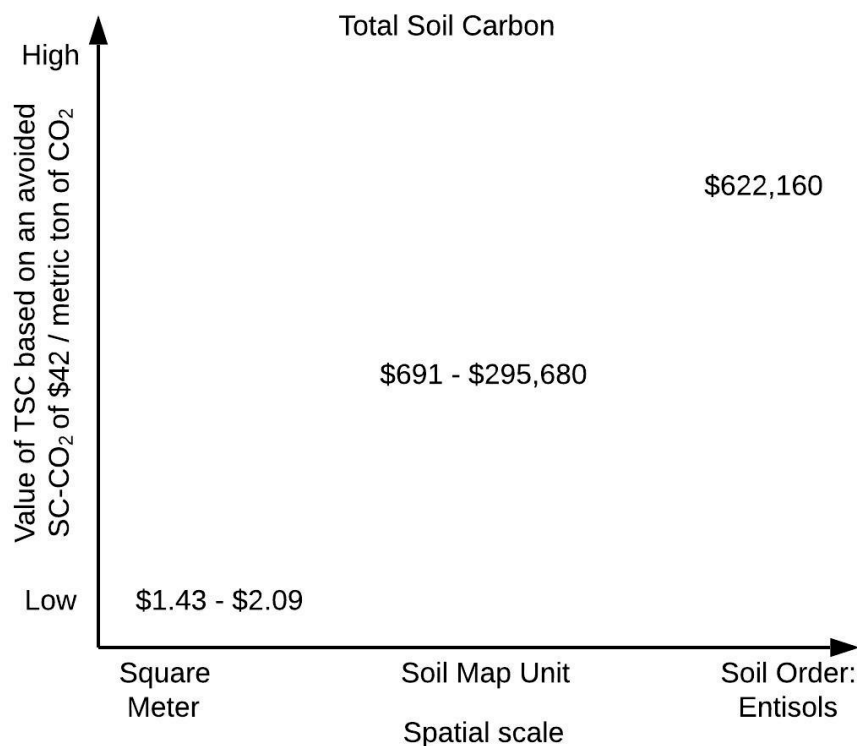


Figure 3. Example of a soil system scale. For the soil order Entisols at the Willsboro Farm (NY), an increasing spatial scale increases the value of total soil carbon (TSC) storage based on interpolated soil core results (based on data from Mikhailova et al., 2016 [22]) and an avoided social cost of carbon emission (SC-CO₂) of USD 42 per metric ton of CO₂ [23].

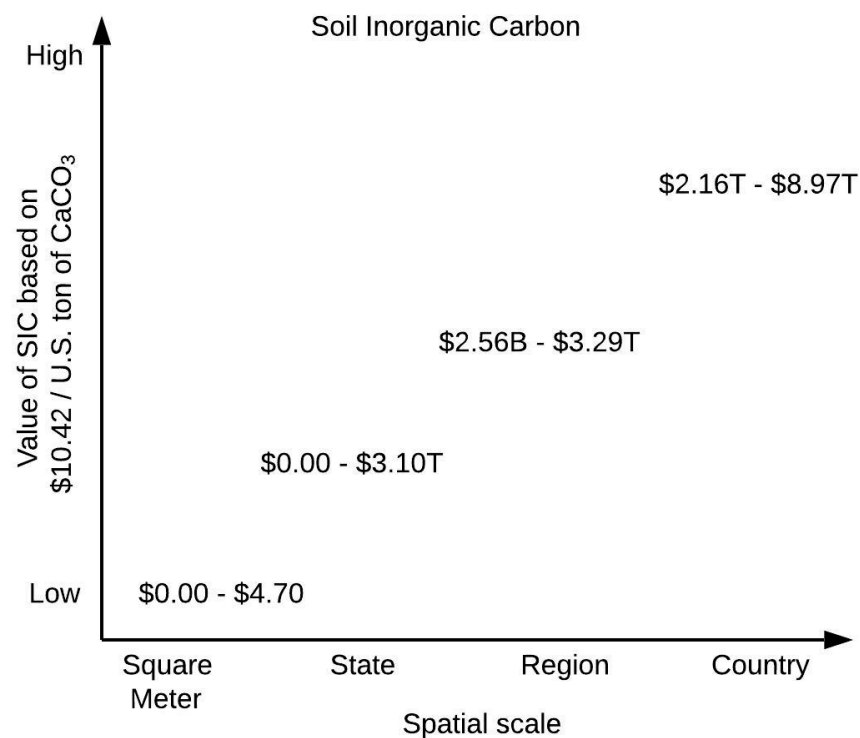


Figure 4. Example of an administrative scale. Replacement cost valuation of soil inorganic carbon (SIC) in the contiguous United States, based on data reported by Guo et al. 2006 [24] and the 2014 U.S. average price of USD 10.42 per U.S. ton of agricultural limestone (CaCO₃) [25] (i.e., symbols used for region spatial scale are USD 2.56B billion, where B = billion = 10⁹; USD 3.29 trillion, where T = trillion = 10¹²).

Zurek and Henrichs (2007) [26] suggested linking environmental assessment scenarios across different geographic scales to better understand linkages across scales. Environmental assessments will depend on the purpose of the scenario exercise [26]. For example, Figure 3 can be used to understand the implications of regulating ES, and how potential social costs of carbon emissions that are avoided at a small scale (starting point) are totaled at larger scales. In the case of provisioning ecosystem services (Figure 4), small scale estimates of SIC replacement costs can be used for larger multiscale scenarios at the state, region, and country extents for potential resource planning and acquisition to replace depleted ES provided by SIC.

Spatial scales are often used in conjunction with temporal scales for spatio-temporal analyses [27]. Different research approaches (experiments, observations, and models) are available at various spatio-temporal scales (Figure 5) to assess the range of potential environmental impacts from short-term, small-scale soil C emissions (e.g., per square meter) to the soil order extent (e.g., soil order of Gelisols on Earth), which can result in a potential tipping point of C emissions with implications to the global climate [27].

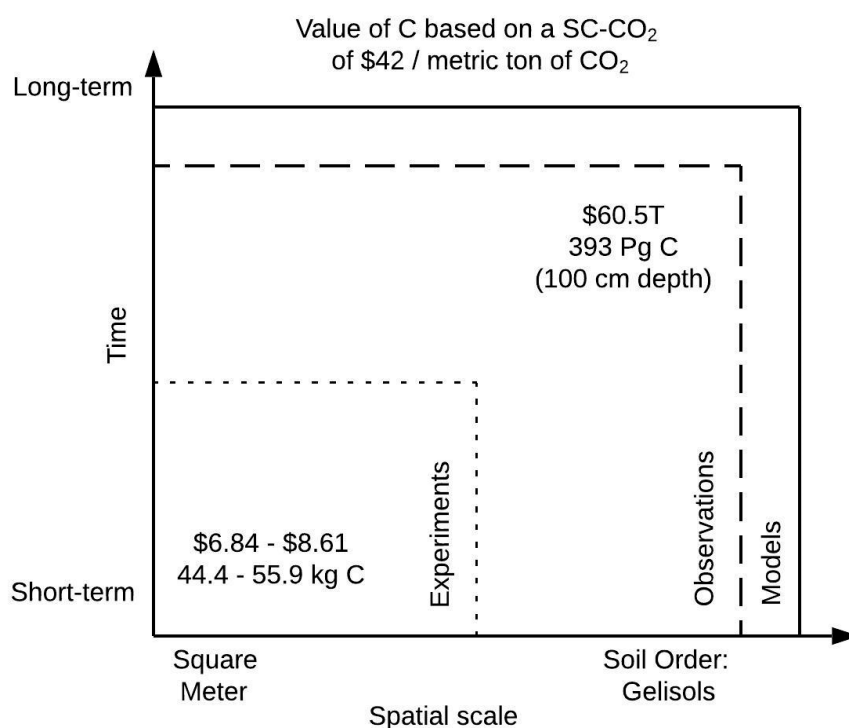


Figure 5. Example of a spatio-temporal scale (based on Reyer et al., 2015 [27]). Total values of soil carbon (C) storage in Gelisols in the upper 100 cm [28] based on an avoided social cost of carbon emissions (SC-CO₂) of USD 42 per metric ton of CO₂ [23] (i.e., USD 60.5 trillion U.S. dollars, where T = trillion = 10¹²).

The soil order Gelisols is of particular concern regarding the tipping point in climate change because it contains large amounts of soil organic matter (SOM), which has been preserved in a frozen and relatively undecomposed state. Gelisols are widely spread in the world's northern regions with permafrost (permanently frozen ground at 0 °C for at least two consecutive years) [29–31]. Climatic change (e.g., warming) in these regions causes the widespread degradation and thawing of permafrost with a subsequent release of carbon dioxide and methane to the atmosphere [30]. There are various model predictions of carbon losses as a result of thawing permafrost, but they typically do not include social cost estimates associated with these losses [32–37]. These predictions (and associated social costs based on an avoided social cost of carbon emissions (SC-CO₂) of USD 42 per metric ton of CO₂ [23]) have various ranges: 7 to 250 Pg C (USD 1.1T to USD 38.5T) by 2100; 121 to 302 Pg C (USD

18.6T to USD 46.5T) by 2200, and 180 to 380 Pg C (USD 27.7T to USD 58.5T) by 2300 for intermediate to high fossil fuel emission scenarios.

The social costs associated with thawing permafrost are not just model predictions but are increasingly being realized. For example, Streletskiy (2019) [29] estimated USD 250B worth of potential damages to infrastructure and structures in northern and eastern Russia from melting permafrost. This estimate was partially realized when, in 2020, melting permafrost was identified as a major factor in a large Siberian fuel spill (15,000 metric tons of diesel fuel were released into the Ambarnaya River and 6000 into the surrounding soil), which caused at least USD 80M (where M = million = 10^6) in environmental damages [38].

3.1.2. Soil System (Time)

The concept of time in soil systems refers to the regolith, which is a layer of loose unconsolidated rock on top of a layer of bedrock [39]. According to Brantley (2008) [39], the interpretation and understanding of soil time depends on the field of study (e.g., geology, biology, etc.) For example, geologists study soil time within a geologic time scale compared to biologists and ecologists who are interested in ecosystem changes within tens to hundreds of years. In view of an ES framework, the concept of time in soil systems depends on the type of ES under consideration. Nutrient cycling and residence time in soils vary with the type of nutrient as well as other major and minor factors. For example, the residence time of soil organic matter (SOM) (global average of 18.5 years) is often life zone dependent, and tends to decrease with an increase in precipitation and temperature (e.g., tundra with an SOM residence time of 213 years compared to wet tropical forests with an SOM residence time of 5 years) [40].

Traditionally, the concept of time in soil systems refers to the degree of weathering and soil development (Table 3). Table 3 illustrates the science-based relationship between soil orders and the market-based valuation of the provisioning ES value (based on liming replacement cost) of SIC. There is a clear relationship between the degree of weathering/soil development and the value of SIC with strongly weathered soils having no SIC to replace because these are highly leached soils with low nutrient contents.

Table 3. Degree of soil development and area-normalized midpoint values of soil inorganic carbon (SIC) storage in the upper 2-m soil depth within the contiguous United States (U.S.) based on midpoint SIC numbers from Guo et al., 2006 [24] and USD 10.42 price per U.S. ton of agricultural lime (CaCO_3) in the U.S. (2014) [25].

Slight ← Degree of Weathering and Soil Development → Strong					
Slight Weathering		Intermediate Weathering		Strong Weathering	
Soil Order	Midpoint SIC Value per Area (\$ m^{-2})	Soil Order	Midpoint SIC Value per Area (\$ m^{-2})	Soil Order	Midpoint SIC Value per Area (\$ m^{-2})
Entisols	0.46	Aridisols	1.52	Spodosols	0.06
Inceptisols	0.49	Vertisols	2.22	Ultisols	0.00
Histosols	0.23	Alfisols	0.41	Oxisols	-
Gelisols	-	Mollisols	1.10		
Andisols	0.00				

These biophysical accounts (science-based) can be integrated with administrative accounts (boundary-based) to show the relationship between weathering/soil development and administrative extent (e.g., state, region) (Table 4). For example, Table 4 reveals that states and regions dominated by slightly and highly weathered soils have no SIC to replace because these soils are either too young to accumulate SIC or too leached of SIC and other nutrients.

Table 4. Integration of biophysical accounts (science-based) and administrative accounts (boundary-based). Degree of soil development and area-normalized midpoint values of soil inorganic carbon (SIC) storage in the upper 2-m soil depth within the contiguous United States (U.S.) based on midpoint SIC numbers from Guo et al., 2006 [24] and USD 10.42 price per U.S. ton of agricultural lime (CaCO_3) in the U.S. (2014) [25].

Slight ← Degree of Weathering and Soil Development → Strong					
Slight Weathering		Intermediate Weathering		Strong Weathering	
State (Region)	Midpoint SIC Value per Area (\$ m ⁻²)	State (Region)	Midpoint SIC Value per Area (\$ m ⁻²)	State (Region)	Midpoint SIC Value per Area (\$ m ⁻²)
Connecticut	0.01	Iowa	1.12	Alabama	0.00
Delaware	0.00	Illinois	0.72	Florida	0.06
Maryland	0.00	Indiana	1.13	Georgia	0.01
Maine	0.00	Michigan	1.17	Kentucky	0.01
New Hampshire	0.00	Minnesota	1.35	Mississippi	0.03
New Jersey	0.00	Missouri	0.11	North Carolina	0.00
New York	0.12	Ohio	0.60	South Carolina	0.02
Pennsylvania	0.00	Wisconsin	0.37	Tennessee	0.00
Rhode Island	0.00	(Midwest)	0.82	Virginia	0.00
Vermont	0.06			(Southeast)	0.01
West Virginia	0.00				
(East)	0.03				

The degree of weathering/soil development places biological and physical constraints on soils, their ES, and any monetary values associated with these services. For example, Mikhailova et al. (2020) [41] have reported the reducing effect of soil-based constraints (e.g., high leaching, low pH, etc.) on the maximum potential SIC sequestration from atmospheric sources in the contiguous U.S. from non-constrained USD 135M/year to soil-based constrained USD 64.36M/year within 54% of the land area. The remaining USD 70.64M associate with Mollisols, Alfisols, and Vertisols will be further reduced to ≤10% due to economic (e.g., crop growth, trade etc.) and socio-political constraints [41,42].

The concept of time in a pedological sense usually applies to natural processes in soils, but anthropogenic (human-affected) changes (e.g., land disturbance, climate change, etc.) have been rapidly transforming soils into “human-natural” bodies [43] with implications for both the natural and human world. Trudgill (2006) [44] points out that modern cultural constructs (e.g., mechanization, urbanization, globalization, etc.) can result in the destruction of soil resources, which may not be renewable on a human time scale because soils are composed of biotic and abiotic components renewable at different timescales [45]. Composting can be used to somewhat regenerate the SOM (biotic) component in a human timescale [46], but the mineral fraction of soil is formed from the weathering of rocks and is governed by a geologic timescale [44]. For example, Mikhailova et al. (2018) [47] reported morphological/diagnostic changes, as well as changes in soil organic carbon (SOC) and SIC, in a 50-year period of cultivation of the Russian Chernozem. Some of the human-induced changes to soils are so profound that Drohan and Farnham (2006) [48] have proposed to recognize rare and threatened soils. Warming of the permafrost is reducing the area of Gelisols at a rapid pace and is threatening its existence as a soil order [49]. Plaza et al. (2019) [50] reported a loss of soil carbon of 5.4% per year at an experimental site in Alaska using direct measurements of permafrost thawing and carbon loss. Such changes have significant socio-economic and monetary consequences, which are not always reported through scientific data. The costs associated with climate change are often considered to be “invisible,” “far more distant,” and the markets have “a tough time” dealing with them [51]. Soils are at risk due to anthropogenic and climate changes, but businesses either “do not or are slow” at connecting these risks with market valuations [51]. The lack of orderly market corrections and “climate risk underpricing” can lead to a “correction all at once,” which can be detrimental for both the market and the environment [51]. This indicates the need for systematic monetary valuations of rapid changes in soil properties (e.g., SOC, SIC, nutrients, etc.) due to human activities using market-

and non-market valuation methods. It should be noted that some climate-change-induced changes in the soils can reach thresholds (such as the disappearance of the soil order of Gelisols), which are likely irreversible [52], and, therefore, not correctable by the market. Monetary valuations, market- and non-market interventions cannot fix the physical world, but they can help human adaptation to its changes. Economic analysis regarding soil actual and/or potential change is important for sustainable soil management to sustain human wellbeing and aid adaptation to dynamic environmental conditions.

3.1.3. Soil System (Degree of Computation and Degree of Complexity)

Valuation starts with the selection of a system (e.g., pedon, horizon, etc.) and soil property or properties to be evaluated. Valuation of soil ES can vary by the degree of computation (qualitative vs. quantitative) and the degree of complexity (mechanistic vs. empirical) [10,11] (Figure 6). Distinctions among these valuations provide examples of their possible use. The selection of an appropriate valuation method will depend on the stakeholders, scope, scale, and other factors. Qualitative models in soil science often use expert knowledge to extrapolate soil information across a landscape [10]. Quantitative models use mathematical models to abstract soil characteristics [10].

Qualitative Empirical	Qualitative Mechanistic
Quantitative Empirical	Quantitative Mechanistic

Figure 6. Possible combinations for the degree of computation and the degree of complexity that can be used in the valuation of soil systems goods and services (SSGS).

Qualitative-empirical valuations can vary from simple verbal valuations of soil ES (e.g., “dirt cheap,” fertile, productive, etc.) [44,53] to soil ES valuation maps. For example, Lobry de Bruyn and Abbey (2003) [54] examined farmers’ values related to soil health and sustainability using interviews with farmers to identify the language and techniques in relation to identifiable themes, such as soil feel, organic matter, soil life, soil texture, soil management, etc. Although farmers were not directly asked about soil-based ES, farmers understood the link between soil health, productive soil, and profitability. Soil maps are also qualitative empirical models which show soil distribution within a landscape based on soil map units (SMUs) that are identified by soil scientists using “a mental version of the soil-landscape model” [55]. Typically, SMU boundaries are based on a combination of limited field data as well as vegetation and topographic associations that are determined by the soil scientist in the field. This qualitative-empirical approach to define soil boundaries then can be associated with soil property data and/or monetary valuation. For example, the legend for the soil map shown in Figure 7 displays monetary soil ES values averaged over the SMUs.

Geospatial technologies (e.g., Geographic Information Systems, etc.) enable soil scientists to use various interpolation techniques to create **qualitative-mechanistic** valuations where field data are used for the extrapolation of point-based information across the farm for soil ES valuations (Figure 8). **Quantitative-empirical valuations** can be demonstrated by an example of a linear regression relationship between soil CO₂ fluxes and soil temperature during winter ($p = 0.009$) under long-term effects of vehicular passages in a no-till corn-soybean rotation on a Crosby silt loam in Central Ohio, USA, with associated daily social costs of carbon dioxide emissions [56] (Figure 9). **Quantitative-mechanistic** valuations can be illustrated by an SOM model (CENTURY) (Parton et al., 1994 [57]), which was used to track SOM dynamics after the conversion of native grassland to long-term (50-year) continuous

fallow [58] (Figure 10). Figure 10 demonstrates that social costs associated with SOC can be added into the model output to inform decision-makers about these costs.

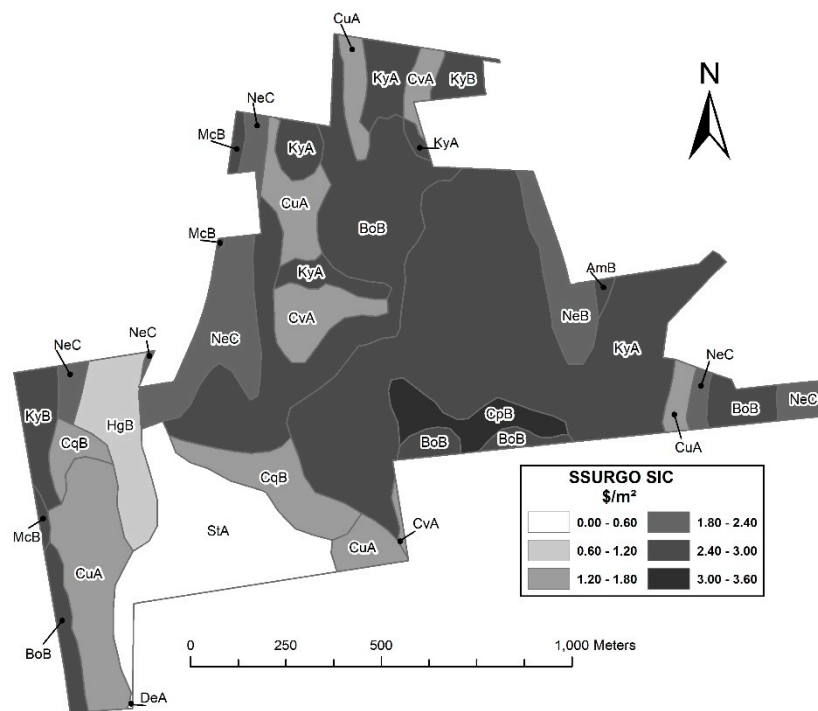


Figure 7. Example of qualitative-empirical valuation of soil inorganic carbon (SIC) based on replacement cost method using the 2014 U.S. average price of \$10.42 per U.S. ton of agricultural limestone (CaCO_3) [25] at the Willsboro Farm, Willsboro, NY from SSURGO results averaged over soil map units (SMUs) (based on data from Mikhailova et al., 2016 [22]).

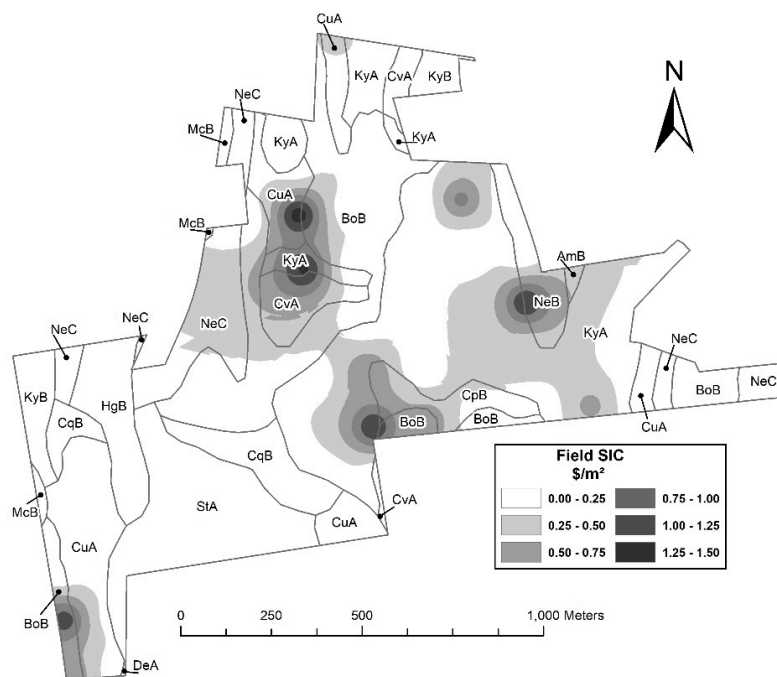


Figure 8. Example of qualitative-mechanistic valuation of soil inorganic carbon (SIC) based on replacement cost method using the 2014 U.S. average price of \$10.42 per U.S. ton of agricultural limestone (CaCO_3) [25] at the Willsboro Farm, Willsboro, NY interpolated from soil core sample results (based on data from Mikhailova et al., 2016 [22]).

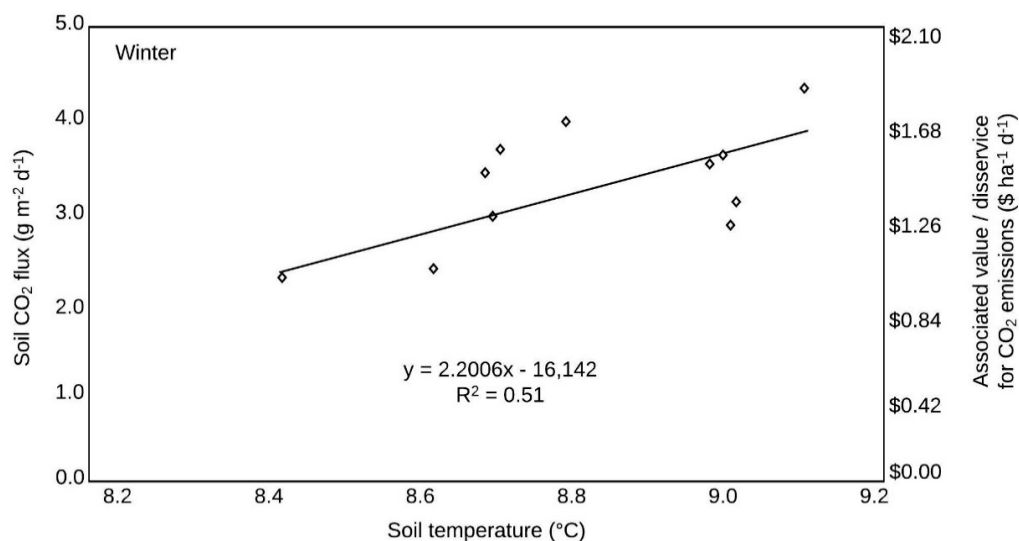


Figure 9. Example of quantitative-empirical valuation using the linear regression relationship between soil CO₂ fluxes and soil temperature during winter ($p = 0.009$) in a no-till corn-soybean rotation on a Crosby silt loam in Central Ohio, USA, under long-term effects of vehicular passages. Regression equation shown in the figure is for soil CO₂ flux vs. soil temperature. The associated values/disservices shown on the right y-axis are based on an avoided SC-CO₂ of USD 42/metric ton of CO₂ [22] (based on data from Yadav et. al., 2019 [56]).

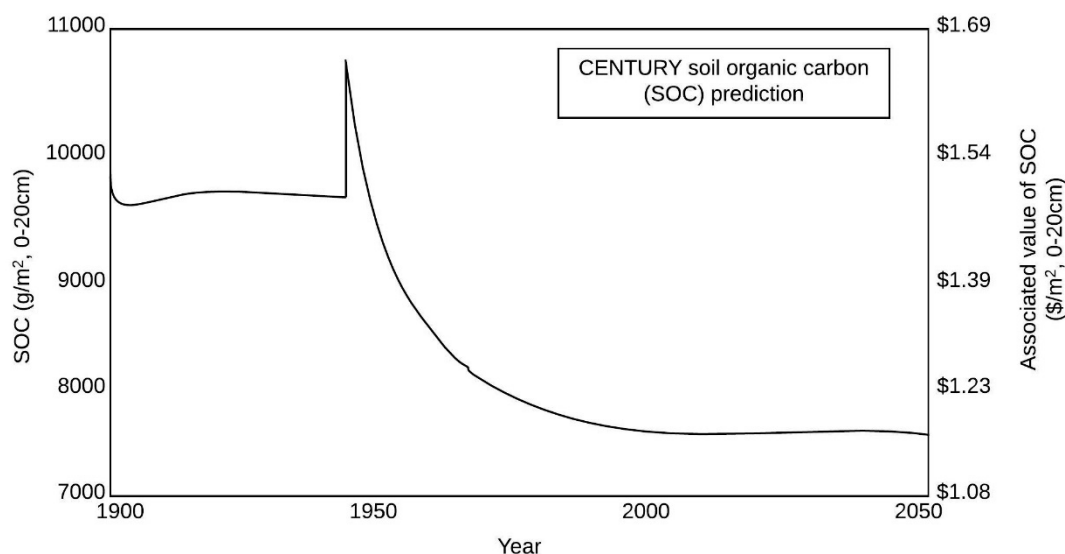


Figure 10. Example of quantitative-mechanistic valuation of soil organic carbon (SOC) simulated by the CENTURY model (Parton et al., 1994 [57]) based on data from Mikhailova et al. (2000) [58]. The associated values shown on the right y-axis are based on an avoided SC-CO₂ of USD 42/metric ton of CO₂ [23].

3.2. Examples of Monetary Valuations Based on Interaction of Pedosphere with Earth's Other Spheres and Organizational Hierarchy of Soil Systems

The pedosphere forms as a result of interactions with Earth's other spheres (atmosphere, biosphere, lithosphere, hydrosphere, ecosphere, and anthroposphere) and exchanges flows of ecosystem goods and services with these spheres (Table 5), which can be of utility to humans [59]. These flows of goods and services are often excluded from monetary valuations of soil ES, even though they are intricately linked with soil properties and functions, and make remarkable monetary contributions to soil ES and disservices (e.g., social costs) (Table 5). Contributions of Earth's spheres to soil ES have a wide range

of applications (e.g., provisioning, maintenance, regulation, etc.) There are various ways to estimate the value of contributions of Earth's spheres to the pedosphere. For example, produced substitutes (e.g., liming, fertilizer materials, etc.) are often used to value the ES provided by Earth's spheres (Table 5), but these substitutes are rarely perfect and can be costly [59]. Future research should examine how to add (without double-counting) these important ES to the monetary valuation of the total supply of ES provided by the soil systems. Disservices (e.g., social costs of carbon dioxide emissions) should be accounted for as well.

Table 5. Examples of monetary valuations based on the interaction of the pedosphere with Earth's other spheres and organizational hierarchy of soil systems.

Earth's Sphere(s)	Example (Valuation)	Type	Soil System (Scale)	Source(s)
Ecosystem Services: Provisioning, maintenance				
Atmosphere, Hydrosphere, Anthroposphere	Atmospheric Ca ²⁺ deposition (market, liming replacement costs)	Abiotc	i + 4	[60]
	Atmospheric Mg ²⁺ deposition (market, liming replacement costs)	Abiotc	i + 4	[61]
	Atmospheric K ⁺ deposition (market, fertilizer replacement costs)	Abiotc	i + 4	[62]
Lithosphere, Anthroposphere	Soil inorganic carbon (SIC)–2-m soil depth (market, liming replacement costs)	Abiotc	i + 4	[15,17]
Ecosystem Services: Regulation				
Atmosphere, Hydrosphere, Anthroposphere	Atmospheric Ca ²⁺ and Mg ²⁺ deposition (avoided social costs of carbon dioxide emissions, SC-CO ₂)	Abiotc	i + 4	[41]
Lithosphere, Anthroposphere	Soil inorganic carbon (SIC)–2-m soil depth (avoided social costs of carbon dioxide emissions, SC-CO ₂)	Abiotc	i + 4	[63]
Biosphere, Anthroposphere	Soil organic carbon (SOC)–2-m soil depth (avoided social costs of carbon dioxide emissions, SC-CO ₂)	Biotic	i + 4	[64]
Biosphere, Lithosphere, Anthroposphere	Total soil carbon (TSC)–2-m soil depth (avoided social costs of carbon dioxide emissions, SC-CO ₂)	Biotic + Abiotic	i + 4	[16]

Note: (i + 4) indicates the levels of scale hierarchy according to the organizational hierarchy of soil systems, where the behavior of a system at the extent scale (i level) can be described in terms of attributes at lower (–) or upper (+) scale levels (adapted from Dijkerman, 1974 [9]).

Despite the various limitations associated with economic valuations of ES provided by the pedosphere and Earth's other spheres, these tools are important in decision making (e.g., benefit-cost analysis, cost effectiveness analysis, etc.) when it comes to natural resource management. Examples of monetary valuations in Table 5 vary in scale, and Brown et al. (2005) [59] point out that economic valuation can be more accurate in evaluating small changes in ES because “existing prices indicate the marginal value of the resource, and the marginal value applies best to a small change in quantity or quality.” Many ES provided from interactions between the pedosphere and Earth's other spheres are provided for free because they are viewed as non-scarce with non-attenuated property rights [59].

4. Discussion

Ecosystem goods, services, and disservices provided by soils are an integral part of business ecosystems [2,65], but they have been narrowly defined (e.g., soil-based, pedosphere-based, etc.) [12,66]

leading to a potential underestimation of their value to human society (Figure 11). Since many ecosystems on Earth have been modified by human activity, there is a need to expand the scope of the soil (and pedosphere) definitions to include the anthroposphere (Figures 2 and 12).

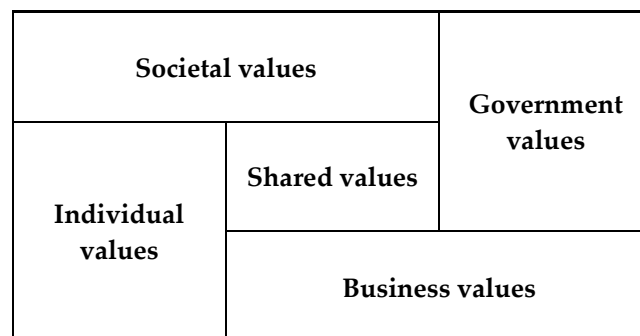


Figure 11. Relationship between different types of stakeholders and their values: societal, government, business, and individual with regards to soil ecosystem goods and services.

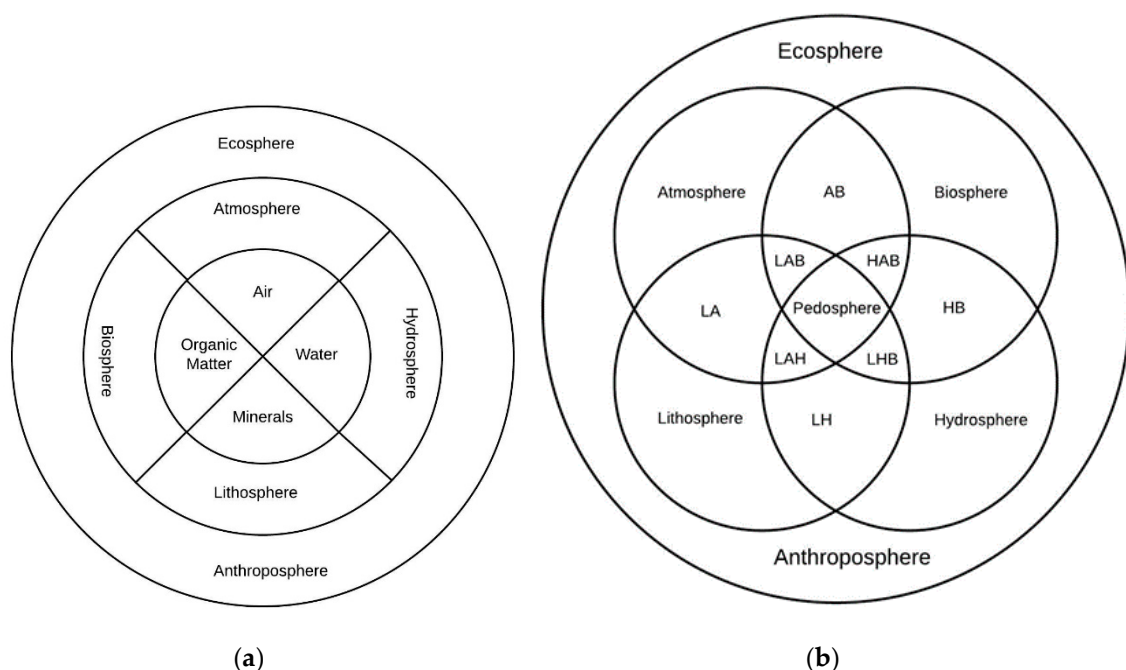


Figure 12. The newly expanded scope of the definition of soil: (a) soil and relationship between soil components from Earth's various spheres; (b) formation of two-sphere, three-sphere, and four-sphere (e.g., pedosphere) systems in nature (A = atmosphere; B = biosphere; H = hydrosphere; L = lithosphere; Ecosphere, and Anthroposphere) (adapted from Mattson, 1938 [7]).

The anthroposphere has impacted all of the Earth's spheres, and it is sometimes difficult to separate the human-derived from natural ES. This review introduces soil systems goods and services (SSGS) as a more inclusive term to describe a combination of anthropogenic and natural goods and services provided by the soils, which are open systems [67] (Figures 2 and 12).

Ecological economics [1] developed the concepts of natural capital, ecosystem goods, and services, which are essential for human wellbeing. According to Guerry et al. (2015) [68], there is a fundamental asymmetry of the most current economic systems which very often reward short-term gains (at the human-scale) at the expense of human wellbeing in the long-term (at the geologic scale). Business and economics are alongside each other, where businesses offer goods and services that generate economic output, while economics determines the supply and demand of these products. Moore (1993) [65] describes business ecosystems with a new ecology of competition between predators and prey,

comparing them to natural ecosystems which can sometimes collapse if the environmental conditions change too rapidly (e.g., comparable to Stephen Jay Gould's evolutionary theory [69] and punctuated equilibrium [70]). According to Moore (1993) [65], successful businesses must attract resources, capital, partners, supplies, and create cooperative networks, which hopefully will be sustainable not only for these businesses but also to the humans they serve.

Soils are complex entities which are organized into soil systems with different organizational hierarchies, which can be integrated within the framework of ecosystem services (Table 1) and business information systems (BIS) (Figure 13). This organizational hierarchy of soil systems can be used by businesses (e.g., BIS, business intelligence (BI), etc.) in the economic valuation of soil ES/ED by scale (e.g., world, continent), time (e.g., soil, geologic), qualitative and quantitative degrees of computation (e.g., mental, verbal, descriptive, mathematical, deterministic, stochastic), and complexity (e.g., mechanistic, empirical) (Table 1). This review introduces soil systems goods and services (SSGS) to human business activity because it describes soil benefits/damages supplied to human societies, governments, businesses, individuals (e.g., farmers, etc.), and shared values between entities (Figure 11). This review has also provided examples of monetary valuations of SSGS based on the interaction of the pedosphere with Earth's other spheres (Table 5).

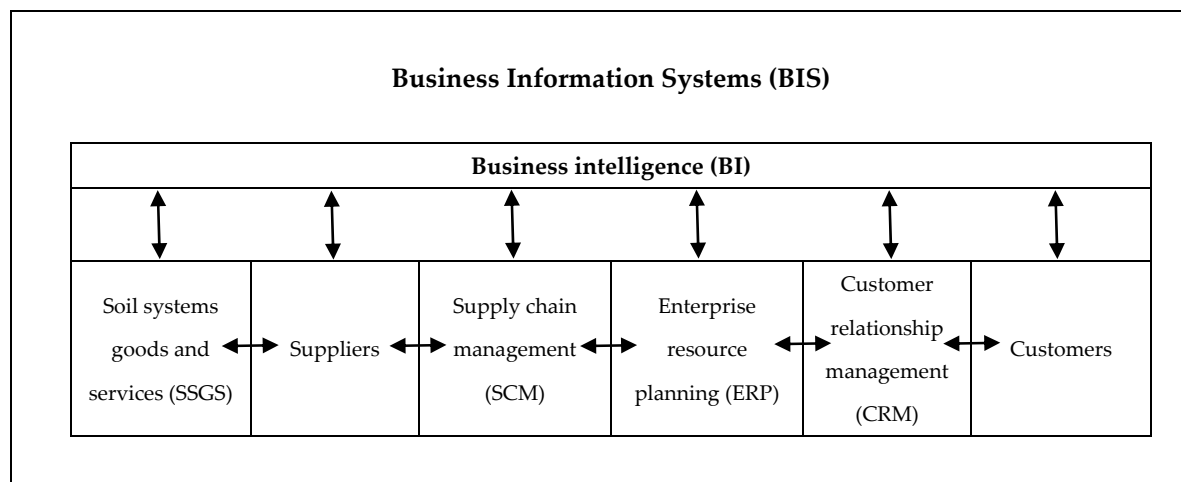


Figure 13. Integration of soil systems goods and services (SSGS) (including goods and services provided by interaction of soil with various Earth's spheres) into the enterprise resource planning (ERP) within the Business Information Systems (BIS) (adapted from Rajnoha et al., 2014 [71]).

Ecosystem goods, services, and disservices (including soil systems ones) are not typically integrated with BIS (Figure 13). In the business environment, suppliers are often associated with humans, but these suppliers rely on raw or transformed ecosystem goods and services from the Earth's spheres. Suppliers (e.g., farmers, etc.) rely on ecosystem goods and services provided by the pedosphere and Earth's other spheres; therefore, they need data and information provided by business intelligence (BI) to make sustainable purchasing decisions which will subsequently impact other parts of the BI system (Figure 13) to deliver to customers more sustainable products. This inclusion will provide businesses with various short-term and long-term benefits including sustainable sources of raw materials, a positive public view of corporate social responsibility [72], climate resilience in supply chain management (SCM) (Figure 13), improved risk analysis and reduction, the opportunity to participate in carbon markets, tax breaks, and many others. A business role is essential in overcoming market failures when it comes to ecosystem goods and services/disservices provided by soil systems at various scales [73]. Although economic valuations of ES are "serious underestimates of infinity" (Costanza et al., 1997) [74], they are useful in identifying unsustainable, inefficient use of resources, and comparing between use options during the decision-making process [73].

5. Conclusions

Current applications of the human-centered ES framework to soils are narrowly defined (e.g., soil-based, pedosphere-based, etc.) and focus on soil properties while treating soil as a closed system. Soils are complex open systems that form from the interaction of Earth's various spheres (atmosphere, biosphere, lithosphere, hydrosphere, ecosphere, and anthroposphere), which contribute to ES/ED but are not accounted for in current ES/ED valuations. Since many ecosystems on Earth have been modified by human activity, there is a need to expand the scope of the soil (and pedosphere) definitions to include the anthroposphere. The anthroposphere has impacted all of the Earth's spheres, and it is sometimes difficult to separate the human-derived from natural ES. The market transforms resources from the Earth's spheres into goods and services/disservices for societal welfare with non-market institutions mediating the human and environmental interactions. These transformations and mediations can result not only in welfare but damages as well. This review proposes to use soil systems and its organizational hierarchy integrated with an ES framework in the economic valuations of soil ES/ED by scale (e.g., world, continent), time (e.g., soil, geologic), qualitative and quantitative degrees of computation (e.g., mental, verbal, descriptive, mathematical, deterministic, stochastic), and complexity (e.g., mechanistic, empirical).

Soil ES/ED can be valued using spatial, temporal, and spatial-temporal scales applicable to both science-based and administrative-based boundaries. In order to value ES/ED, data are required; however, humans can only do experiments over small-scale areas using a short-term temporal scale. This experimental data can be used to help parameterize models that can make predictions over large geographic extents and longer time frames to help access the full potential economic impact of soil change (e.g., thawing of permafrost in Gelisols and the massive release of various greenhouse gases).

Time in soil systems often shows a relationship between the degree of soil weathering and the value of ES/ED. The degree of weathering/soil development puts bio-physical constraints on soils, its ES/ED, and monetary values associated with these services. This review demonstrated the effect of the degree of weathering on the value of provisioning ES from SIC using biophysical and administrative accounts with strongly weathered soils having essentially no SIC available in the soil. This would influence the fertilizer and liming investments required for agriculture. There is a common misconception that all soils can sequester carbon, but carbon sequestration potential is often directly limited by the degree of weathering. The pedological concept of time refers to natural soil processes, however anthropogenic pressures are rapidly transforming soils into "human-natural" bodies. These human impacts can result in the destruction of soil resources, which cannot be renewed on a human timescale.

Valuations of soil ES/ED can be done with various degrees of computation (quantitative or qualitative) and complexity (mechanistic or empirical), and examples of these valuations range from soil maps to the CENTURY model simulation of soil carbon dynamics and associated social costs of carbon dioxide emissions. This review provides examples of monetary valuations of ES/ED based on the interaction of the pedosphere with Earth's other spheres using various market and non-market valuation methods (e.g., liming replacement costs, fertilizer replacement costs, etc.).

Ecosystem goods and services are not typically integrated with BIS. Suppliers rely on ecosystem goods and services provided by the pedosphere and Earth's other spheres and need information provided by business intelligence (BI) to identify sustainable purchasing options which will deliver to customers more sustainable products. The integration of BIS with ES/ED valuations will provide businesses with benefits including more sustainably sourced raw materials, a more positive public perception, as well as climate resilience and risk reduction in supply chain management (SCM), the ability to participate in carbon markets, and other related regulatory incentives. This review introduces soil systems goods and services (SSGS) as a more inclusive term to describe the combination of anthropogenic and natural goods and services/disservices provided by soils. Although monetary valuations can be useful in human decision making, changes in soil systems are governed by natural processes and human induced changes may not be reversible on a human time scale.

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