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Soil Diversity (Pedodiversity) and Ecosystem Services

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Abstract: Soil ecosystem services (ES) (e.g., provisioning, regulation/maintenance, and cultural) and ecosystem disservices (ED) are dependent on soil diversity/pedodiversity (variability of soils), which needs to be accounted for in the economic analysis and business decision-making. The concept of pedodiversity (biotic + abiotic) is highly complex and can be broadly interpreted because it is formed from the interaction of atmospheric diversity (abiotic + biotic), biodiversity (biotic), hydrodiversity (abiotic + biotic), and lithodiversity (abiotic) within ecosphere and anthroposphere. Pedodiversity is influenced by intrinsic (within the soil) and extrinsic (outside soil) factors, which are also relevant to ES/ED. Pedodiversity concepts and measures may need to be adapted to the ES framework and business applications. Currently, there are four main approaches to analyze pedodiversity: taxonomic (diversity of soil classes), genetic (diversity of genetic horizons), parametric (diversity of soil properties), and functional (soil behavior under different uses). The objective of this article is to illustrate the application of pedodiversity concepts and measures to value ES/ED with examples based on the contiguous United States (U.S.), its administrative units, and the systems of soil classification (e.g., U.S. Department of Agriculture (USDA) Soil Taxonomy, Soil Survey Geographic (SSURGO) Database). This study is based on a combination of original research and literature review examples. Taxonomic pedodiversity in the contiguous U.S. exhibits high soil diversity, with 11 soil orders, 65 suborders, 317 great groups, 2026 subgroups, and 19,602 series. The ranking of "soil order abundance" (area of each soil order within the U.S.) expressed as the proportion of the total area is: (1) Mollisols (27%), (2) Alfisols (17%), (3) Entisols (14%), (4) Inceptisols and Aridisols (11% each), (5) Spodosols (3%), (6) Vertisols (2%), and (7) Histosols and Andisols (1% each). Taxonomic, genetic, parametric, and functional pedodiversity are an essential context for analyzing, interpreting, and reporting ES/ED within the ES framework. Although each approach can be used separately, three of these approaches (genetic, parametric, and functional) fall within the "umbrella" of taxonomic pedodiversity, which separates soils based on properties important to potential use. Extrinsic factors play a major role in pedodiversity and should be accounted for in ES/ED valuation based on various databases (e.g., National Atmospheric Deposition Program (NADP) databases). Pedodiversity is crucial in identifying soil capacity (pedocapacity) and "hotspots" of ES/ED as part of business decision making to provide more sustainable use of soil resources. Pedodiversity is not a static construct but is highly dynamic, and various human activities (e.g., agriculture, urbanization) can lead to soil degradation and even soil extinction.

Keywords: climate change; extinction; food; land use; market; pedocapacity; security; soil capacity

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1. Introduction

Soils are complex, dynamic bodies that form from interactions among the Earth's various spheres (atmosphere, biosphere, lithosphere, hydrosphere) within the ecosphere,

which is modified by the anthroposphere (the sphere of human influence) (Figure 1a). The uniqueness of soils is that they are not discrete entities; but instead, soils form a continuum (pedosphere), which varies both with depth and horizontal distance [1,2]. The concept and measures of soil diversity/pedodiversity (variability of soils) are highly complicated because pedodiversity (biotic + abiotic) results from atmospheric diversity (abiotic + biotic), biodiversity (biotic), hydrodiversity (abiotic + biotic), and lithodiversity (abiotic) within the ecosphere, which is modified by the anthroposphere (Figure 1b). According to Mattson, 1938 [3], soils can be a product of two- or three-sphere combinations; therefore, pedodiversity can be based on two- or three-sphere combinations as well (Figure 1b). A definition of pedodiversity from Odeh (1998) [4] is "variability of soil in a specific area or region, as determined by its constitution, types, attributes and the conditions under which the various types were formed." The concept of pedodiversity (biotic + abiotic) can be widely interpreted based on a range of definitions, depending on the type of pedodiversity (e.g., taxonomic, genetic, parametric, and functional) [5] (Table 1). Pedodiversity is influenced by intrinsic (within pedodiversity itself) and extrinsic factors (environmental factors from atmosphere, biosphere, lithosphere, the hydrosphere, ecosphere, and anthroposphere that control and influence pedogenesis) (Figure 1) [6].

Previous studies have examined the concept and measures of pedodiversity from a pedological point of view and concluded its importance for the sustainable use of soil resources [7–11]. Ibáñez et al. (1995) [11] examined pedodiversity from an ecological point of view and concluded that "patterns of biodiversity, geomorphological diversity and pedodiversity have great similarities, suggesting that there are universal regularities common to the organization of biotic and abiotic ecological structures."

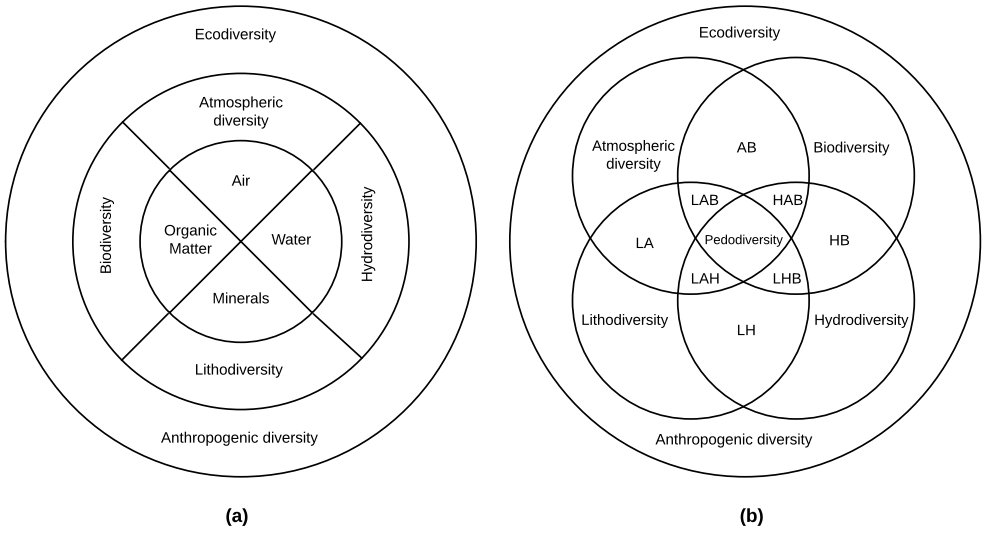

Figure 1. The scope of soil diversity (pedodiversity) (biotic + abiotic): (**a**) soil and relationship between soil components from the Earth's various diverse spheres; (**b**) formation of two-sphere, three-sphere, and four-sphere (e.g., pedodiversity) systems in nature (**A** = atmospheric diversity (abiotic + biotic); **B** = biodiversity (biotic); **H** = hydrodiversity (abiotic + biotic); **L** = lithodiversity (abiotic) (adapted from Mattson, 1938 [3]; Mikhailova et al., 2020 [12]; Ibáñez et al., 1998 [13]). Pedodiversity is influenced by intrinsic (within soil itself) and extrinsic (environmental) factors (e.g., atmospheric deposition).

Guo et al. (2003) [14] reported the taxonomic structure, spatial distribution, and relative abundance of soils in the contiguous United States (U.S.) by order (11), suborder (52), great groups (232), subgroups (1175), family (6226), and series (13,129) using the STATSGO (1997 version) database. Amundson et al. (2003) [2] examined "natural" soil diversity and land use in the U.S. based on U.S. Department of Agriculture (USDA) Soil Taxonomy [15], the State Soil Geographic (STATSGO) dataset (1997), and two numerical parameters: series density and series abundance. The same study quantified rare, unique, and endangered soils in the U.S. and listed directions for future research, including establishing the societal

value of undisturbed soils, monitoring changes in pedodiversity, and focusing conservation efforts on soil diversity "hotspots" [2].

Table 1. Examples of soil diversity (pedodiversity) types.

Types of Soil Diversity (Pedodiversity)	Examples
Taxonomic (diversity of soil classes)	USDA Soil Taxonomy (e.g., soil order, series)
Genetic (diversity of genetic horizons)	A, B, etc.
Parametric (diversity of soil properties)	Soil organic matter (SOM), calcium carbonate ($CaCO_3$), etc.
Functional (soil behavior under different use)	Interpretive models to predict soil behavior

Soil and its diversity (pedodiversity) play significant roles in underlying ecosystem goods and services for humans [16–18], who have developed a human-centered ecosystem services framework [19] as an approach for valuing these goods and services in both economic and non-economic ways [20]. In fact, pedodiversity can be considered an ecosystem good and service in its own right [2]. According to Bartkowski (2017) [21], economic valuations of diversity are rare and often focus primarily on biodiversity [22,23]. Previous research on biodiversity and its significance lists the following benefits [24]: (1) biodiversity supports healthy ecosystems by increasing ecosystem stability, while the loss of biodiversity can reduce their function and efficiency; (2) the relationship between the loss of biodiversity and ecosystem function is not linear, with greater impact as the loss of biodiversity increases; (3) both variety of species and key individual species are critical for ecosystem functioning, with diversity across trophic levels potentially having a more important function compared to species within trophic levels. From a business point of view, Stephenson (2012) [25] describes the utility of biodiversity to: (1) identify the stock, its physical state, and spatial patterns of biodiversity in relation to the key ecosystem services (e.g., water and carbon sequestration), which are at risk and have a high value (e.g., social, economic); (2) assess biodiversity trends, high-risk biodiversity loss with its key drivers as well as a reference point against which progress can be measured; (3) develop a long-term coordinated vision assessing trade-offs and potential synergies including cost-benefit analyses; (4) identify and implement a cost-effective policy option; and (5) monitor progress towards objectives and reviewing and revising policies over time based on the progress.

Ecosystem services (ES) are goods and services provided by functioning ecological systems that directly and/or indirectly benefit human populations (e.g., food and climate regulation) [16–18]. At the same time, however, functioning ecological systems also can present detrimental effects for humans or so-called ecosystem disservices (ED) (e.g., social cost of carbon dioxide) [12]. Adhikari and Hartemink (2016) [16] examined the link between soil properties and ES without including the concept of pedodiversity and its measures in their literature review. Chandler et al. (2018) [26] proposed integrating soil analyses within frameworks for ES and the organizational hierarchy of soil systems. Mikhailova et al. (2020) [12] pointed out that applications of ES to soils are narrowly defined (e.g., soil-based, pedosphere-based), treating soil as a closed system instead of an open system, which requires a soil systems-based approach to ES. Mikhailova et al. (2020) [12] suggested including the contributions of the Earth's spheres (atmosphere, biosphere, hydrosphere, lithosphere, ecosphere, and anthroposphere) in the economic analysis of soil ES. Because most soils have been modified by humans, Mikhailova et al. (2020) [12] examined the business side of ecosystem services of soil systems and proposed to use the term "soil systems goods and services" (SSGS) instead of "soil ecosystem goods and services." Applications of biodiversity concepts and their measures to pedodiversity can be problematic, because they have not been designed explicitly for pedodiversity and its associated ES/ED valuations. Pedodiversity concepts and measures in their current forms have not been considered in ES/ED valuations and business decision making. Most likely, the types of pedodiversity and measurement approaches listed in Table 1 cannot be used

solely on their own in ES/ED but must be applied in combination with each other or even all together concerning specific ES/ED within a particular administrative extent.

The objective of this study is to illustrate the application of pedodiversity concepts and measures to value ES/ED, with examples provided primarily from the contiguous U.S., its administrative units, and the USDA Soil Taxonomy system of soil classification. Although the focus of the examples is on the U.S., the applications and measures described should be readily applicable to other geographic areas and market economies.

2. Materials and Methods

2.1. Data Compilation and Analyses

Soil survey information (including soil orders, suborders, great groups, subgroups, families and series) was obtained from Soil Survey Geographic (SSURGO) Database (2020) [27]. The information for each state in the contiguous U.S. was extracted using Zonal Statistics (Tables) spatial analyst tool in ArcGIS® Pro 2.6 (ESRI, Redlands, CA, USA), while the information for the regions and the Land Resource Regions (LRR) was computed by developing a Structured Query Language (SQL) code that was utilized in SSURGO webpage (https://sdmdataaccess.nrcs.usda.gov/, accessed on 10 October 2020). All this information was then used to create a Microsoft Excel file with the soil survey information for each boundary. Examples of soil ES/ED and their monetary valuations were obtained from various literature sources using the Web of Science [28]. These examples encompass the three major groups of ES commonly used in the literature: provisioning, regulation/maintenance, and cultural [29].

2.2. The Accounting Framework

Table 2 provides a conceptual overview of the accounting framework for 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. A conceptual overview of the accounting framework for a systems-based approach in the ecosystem services (ES) valuation of various soil ecosystem goods and services based on soil diversity (pedodiversity) (adapted from Groshans et al., 2018 [30]).

STOCKS		**FLOWS**		**VALUE**
Biophysical Accounts (Science-Based)	**Administrative Accounts (Boundary-Based)**	**Monetary Accounts**	**Benefits/Damages**	**Total Value**
Soil extent:	Administrative extent:	Ecosystem good(s) and service(s):	Sector:	Types of value:
Examples of valuations based on soil diversity (pedodiversity)				
Examples of valuations based on the interaction of soil diversity (pedodiversity) and the Earth's spheres				
Soil diversity (pedodiversity), organizational hierarchy of soil systems	Administrative, organizational hierarchy	Provisioning, regulation/ maintenance and cultural	Environment, agriculture, industry, etc.	Market and non-market valuations

2.3. The Total Economic Value (TEV) Framework with Insurance Value

Table 3 provides a conceptual overview of the total economic value (TEV) framework with insurance value adapted from various sources to provide a general explanation of valuation methods used in the examples primarily from the U.S., which may apply to other market economies. It should be noted that the relevance and applications of economic valuation to soil systems are not always clearly defined and can be subject to interpretation.

Table 3. The total economic value (TEV) framework with insurance value (adapted from Nimmo-Bell (2011) [31], NZIER, 2018 [32], Baveye et al., 2016 [18], and Bartkowski et al., 2020 [20]).

Total Economic Value (TEV)						
Instrumental Value (Benefits to Humans)						**Intrinsic Value (Benefits to Nature)**
Use Values					**Insurance Value**	**Unknown**
Actual Use Values		**Passive Use Values**				
Direct Use Value (extractive and non-extractive uses)	**Indirect Use Value** (functional benefits)	**Altruistic Value** (for others)	**Bequest Value** (for others)	**Existence Value** (for life)	**The amount available to replace lost value**	
Consumptive and non-consumptive (e.g., agriculture)	e.g., ecosystem services	e.g., preserving resource so others can use it now	e.g., preserving resource so others can use it in the future	e.g., resource preservation	e.g., buffering capacity	
Option Value						
← **Decreasing Tangibility of Value to User** →						

3. Results

3.1. Intrinsic Factors: Examples of Valuations Based on Pedodiversity and Ecosystem Services

3.1.1. Examples of Taxonomic Pedodiversity and Ecosystem Services in the Contiguous U.S.

Pedodiversity is influenced by intrinsic (within the soil) factors, including taxonomic, genetic, parametric, and functional pedodiversity, which provide an important context for analyzing, interpreting, and reporting ES/ED within the ES framework. Although each approach can be used separately, three of these approaches (genetic, parametric, and functional) fall within the "umbrella" of taxonomic pedodiversity, which separates soils based on properties important for potential use. Pedodiversity in the U.S. can be quantified and valued within the framework of the USDA Soil Taxonomy (Soil Survey Staff, 1999 [15]), an international system of soil classification, with the purpose of organizing soils into groups with similar properties. Soil individual (a three-dimensional body) is the object of soil classification in Soil Taxonomy, which is based on a nested and hierarchical system with six taxonomic categories: order, suborder, great group, subgroup, family, and series (e.g., Cecil (Fine, kaolinitic, thermic Typic Kanhapludults) (Table 4). Table 4 demonstrates an example of criteria and sequence of taxonomic categories used to classify mineral soils (this sequence is different for organic soils and soils with permafrost). Soil Taxonomy is the basic system of soil classification for making and interpreting soil surveys, which can be used with the ES framework (Figure 2, Table 5).

Table 4. Example of criteria and sequence of taxonomic categories used to classify soils.

Taxonomic Category	Explanation	Example	Increase in Specificity
Order	Highest category, diagnostic horizons	Ultisols	
Suborder	The difference in moisture regimes	Udults	
Great Group	Presence of key horizons	Hapludults	
Subgroup	Proximity to "central concept"	Typic Kanhapludults	
Family	Particle-size classes and their substitutes	fine	
	Human-altered and human-transported material classes		
	Mineralogy classes	kaolinitic	
	Cation-exchange activity classes (CEC/% clay)		
	Calcareous and reaction classes		
	Soil temperature classes	thermic	
	Soil depth classes		
	Rupture-resistance classes		
	Classes of coatings on sands		
	Classes of permanent cracks		
Series	Smallest unit	Cecil	

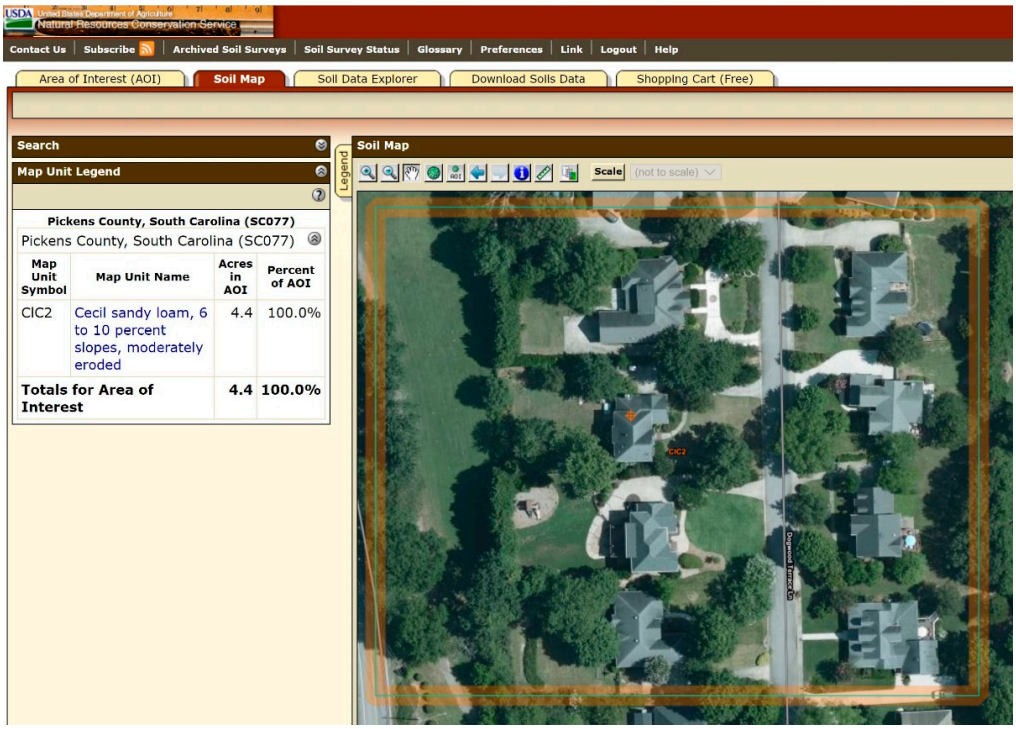

Figure 2. Example of a soil map generated with Web Soil Survey (WSS) [33] showing soil cover and land use.

Table 5. Example of different soil properties (e.g., physical soil properties) in the Web Soil Survey (WSS) [33].

Map Symbol and Soil Name	Depth	Sand	Silt	Clay	Organic Matter
	In	Pct	Pct	Pct	Pct
ClC2-Cecil sandy loam, 6 to 10 percent slopes, moderately eroded	0-5	59-70-75	10-20-35	5-10-15	0.5-0.5-1.0
	5-54	15-30-40	6-16-26	35-54-59	0.0-0.1-0.5
	54-80	35-40-50	17-27-40	20-33-34	0.0-0.1-0.5

Note: Three values are provided to identify the expected Low (L), Representative (R), and High (H).

Pedodiversity data in soil surveys and databases (e.g., maps, depth of soil horizons, and soil properties) are useful in business applications because they provide information about the pedodiversity of soil capital and the necessary data to calculate stocks of soil biotic

(e.g., organic carbon) and abiotic (e.g., sand, silt, clay, and calcium carbonate) resources within different extents (e.g., science-based, administrative based, or in combination; by soil depth, by soil horizon, etc.). This information is essential for various ES/ED applications (e.g., provisioning and regulating) and even cultural ecosystem services. The names of some soil series used in the U.S. reflect cultural and historical heritage. For example, the name of New Mexico State Soil "Penistaja" is derived from the Navajo name meaning "forced to sit" [34].

The most general category of soil orders in Soil Taxonomy provides a useful framework and description of soil, which can be applied to describe the soil stock and its composition, its potential for delivering key ES, and constraints (ED) at several soil system scales, for example, world, continent, region, country, and watershed (Table 6). General characteristics and constraints of these soil orders provide both qualitative and quantitative measures regarding the ability of these soils to supply ES/ED within a geographic area.

Table 6. Soil diversity (pedodiversity) is expressed as taxonomic diversity at the level of soil order and ecosystem services types.

	Stocks	**Ecosystem Services**		
Soil Order	**General Characteristics and Constraints**	**Provisioning**	**Regulation/Maintenance**	**Cultural**
	Slight Weathering			
Entisols	Embryonic soils with ochric epipedon	x	x	x
Inceptisols	Young soils with ochric or umbric epipedon	x	x	x
Histosols	Organic soils with ≥20% of organic carbon	x	x	x
Gelisols	Frozen soils with permafrost	x	x	x
Andisols	Volcanic soils	x	x	x
	Intermediate Weathering			
Aridisols	Dry soils. Common in desert areas	x	x	x
Vertisols	Soils with swelling clays	x	x	x
Alfisols	Clay-enriched B horizon with B.S. ≥ 35%	x	x	x
Mollisols	Carbon-enriched soils with B.S. ≥ 50%	x	x	x
	Strong Weathering			
Spodosols	Coarse-textured soils with albic and spodic horizons	x	x	x
Ultisols	Highly leached soils with B.S. < 35%	x	x	x
Oxisols	Highly weathered soils rich in Fe and Al oxides	x	x	x

Note: B.S. = base saturation.

Taxonomic pedodiversity in the contiguous U.S. exhibits a wide range of soil diversity, with 11 soil orders, 65 suborders, 317 great groups, 2026 subgroups, and 19,602 series (Table 7). Table 7 shows the "soil order abundance"—total area of each soil order within the contiguous U.S. based on Soil Survey Geographic (SSURGO) Database (2020) with the following distribution: (1) Mollisols (27%), (2) Alfisols (17%), (3) Entisols (14%), (4) Inceptisols and Aridisols (11% each), (5) Spodosols (3%), (6) Vertisols (2%), and (7) Histosols and Andisols (1% each). In terms of the degree of weathering: slightly-weathered soils are 27%, intermediately-weathered soils are 58%, and strongly-weathered soils are 15% of the total area.

Information about taxonomic pedodiversity can be linked to various ES/ED. In terms of provisioning ES, 58% of the contiguous U.S. is occupied by soils with high and moderate fertility status (without taking into account the past and present land use). It also can be used to analyze the patterns of value for regulating ES. Mikhailova et al. (2019) [35] provided a valuation of soil organic carbon (SOC) stocks in the contiguous U.S. based on taxonomic pedodiversity and the avoided social cost of carbon (SC-CO_2) emissions, which varied by the degree of soil weathering as indicated by soil order information. This study found the following distribution of SC-CO_2 contribution within the contiguous U.S.: slightly-weathered soils (38%), intermediately-weathered soil (51%), and strongly-

weathered soils (11%). In another example, according to Mikhailova et al. (2019) [36], Mollisols have the highest total soil carbon (TSC, soil organic + soil inorganic carbon) storage midpoint value ($7.78T) based on the social cost of carbon (SC-CO_2) and avoided emissions provided by carbon sequestration, which is about 30% of the total midpoint value for the contiguous U.S. These types of analyses are useful in identifying soil "hotspots" with regards to various ES/ED applications at different scales which has the potential to be managed with precision agriculture [2,37]. It can be concluded that taxonomic pedodiversity provides an important context for analyzing, summarizing, and presenting soil data for ES/ED applications.

Soil series is also a useful taxonomic category to describe pedodiversity regarding ES/ED at more detailed scales (e.g., farm and field), and this category is closely allied to interpretive uses (e.g., suitabilities and limitations for crop production and construction) (Table 7). Soil series consist of pedons that are grouped together based on similarity in pedogenesis, soil chemistry, and physical properties [38]. The number of soil series within the soil extent can describe its diversity (Table 7). According to Table 7, Mollisols have the highest number of soil series (5569), followed by Entisols (3700). Amundson et al. (2003) [2] proposed to apply a commonly used biodiversity parameter ("species density") to soil diversity, which they called a "series density" parameter (number of series divided by 100,000 ha) (Table 7).

Table 7. Soil diversity (pedodiversity) is expressed as the number of soil classes (taxonomic pedodiversity) within soil orders in the contiguous United States (U.S.) based on Soil Survey Geographic (SSURGO) Database (2020) [27].

Soil Order	Suborders	Great Groups	Subgroups	Series	Series Density
Slight Weathering					
Entisols	25	56	246	3700	3.5
Inceptisols	26	67	386	3610	4.6
Histosols	7	25	73	334	3.1
Gelisols *	2	2	2	2	-
Andisols	13	26	90	642	9.3
Intermediate Weathering					
Aridisols	17	44	283	2374	2.9
Vertisols	7	31	101	394	3.0
Alfisols	14	49	331	3242	2.5
Mollisols	23	55	422	5569	2.8
Strong Weathering					
Spodosols	9	26	92	591	2.4
Ultisols	9	27	107	1091	1.3
Oxisols	-	-	-	-	-
Totals	**65**	**317**	**2026**	**19,602**	**2.7**

Note: * Soil order of Gelisols was reported for the state of Washington with an area of 11 m^2. Series density equals the number of series divided by 100,000 ha.

Taxonomic pedodiversity can also be used within administrative boundaries (e.g., Land Resource Regions, LRRs) (Table 8). Land Resource Regions (LRRs) are defined by the USDA using major land resource area (MLRA) and agricultural markets, which are denoted using capital letters (A, B, C, etc.; see Table 8 notes). The contiguous U.S. comprises 20 of the 28 LRRs. The LRRs with the highest number of soil orders are: (1) A—Northwestern Forest, Forage and Specialty Crop Region (11), and (2) E—Rocky Mountain Range and Forest Region (10). The LRRs with the highest number of series are: (1) D—Western Range and Irrigated Region (5739), (2) E—Rocky Mountain Range and Forest Region (3611), and (3) A—Northwestern Forest, Forage, and Specialty Crop Region (2065). The LRRs with the highest series density are: (1) A—Northwestern Forest, Forage and Specialty Crop Region (11.4), and (2) C—California Subtropical Fruit, Truck and Specialty Crop

Region (8.6), and (3) S—Northern Atlantic Slope Diversified Farming Region (7.2). According to Table 7, the average series density for the contiguous U.S. is 2.7 series/100,000 ha, and slightly-weathered soils have the highest series densities with Andisols in the lead (9.3 series/100,000 ha). Variation in soil series density can relate to ES/ED, but it depends on the properties of the soil series within an area and the interpretive uses. Soil ES related to agriculture can be reduced in some areas by high soil variability, which can impact the soil productivity at the farm scale. For example, in areas with soils derived from glacial materials, the high variability of soil properties can occur at the field scale limiting agricultural use and productivity.

Table 8. Soil diversity (pedodiversity) is expressed as the number of soil classes (taxonomic pedodiversity) within Land Resource Regions (LRRs) for the contiguous United States (U.S.) Soil Survey Geographic (SSURGO) Database (2020) [27].

LRRs	Orders	Suborders	Great Groups	Subgroups	Series	Series Density
A	11	53	159	567	2065	11.4
B	8	41	108	377	1482	5.7
C	9	38	107	294	1264	8.6
D	9	51	185	977	5739	4.5
E	10	52	165	783	3611	6.9
F	7	25	69	243	865	2.5
G	7	33	94	369	1957	3.8
H	8	27	69	270	1080	1.8
I	6	22	57	184	538	3.2
J	6	22	58	214	606	4.3
K	7	24	61	267	1265	4.2
L	6	19	53	185	819	6.8
M	8	31	89	352	1834	2.6
N	8	31	88	300	1700	2.8
O	7	17	43	128	346	3.7
P	8	27	88	316	1468	2.2
R	7	27	82	242	1321	4.4
S	8	23	66	192	712	7.2
T	9	29	93	295	854	3.7
U	8	22	50	127	279	3.3
Totals	**11**	**65**	**317**	**2026**	**19,602**	**2.7**

Note: A = Northwestern Forest, Forage and Specialty Crop Region; B = Northwestern Wheat and Range Region; C = California Subtropical Fruit, Truck and Specialty Crop Region; D = Western Range and Irrigated Region; E = Rocky Mountain Range and Forest Region; F = Northern Great Plains Spring Wheat Region; G = Western Great Plains Range and Irrigated Region; H = Central Great Plains Winter Wheat and Range Region; I = Southwest Plateaus and Plains Range and Cotton Region; J = Southwestern Prairies Cotton and Forage Region; K = Northern Lake States Forest and Forage Region; L = Lake States Fruit, Truck and Dairy Region; M = Central Feed Grains and Livestock Region; N = East and Central Farming and Forest Region; O = Mississippi Delta Cotton and Feed Grains Region; P = South Atlantic and Gulf Slope Cash Crops, Forest and Livestock Region; R = Northeastern Forage and Forest Region; S = Northern Atlantic Slope Diversified Farming Region; T = Atlantic and Gulf Cost Lowland Forest and Crop Region; U = Florida Subtropical Fruit, Truck Crop and Range Region. Series density equals the number of series divided by 100,000 ha.

Taxonomic pedodiversity within administrative boundaries (e.g., LRRs) can be broken down by soil orders with their corresponding areas for qualitative and quantitative assessments of soil stocks for ES/ED assessments (Table 9). For example, for the LRR A—Northwestern Forest, Forage and Specialty Crop Region, the area of soil orders were distributed as follows: Entisols (3%), Inceptisols (37%), Histosols (0%), Andisols (20%), Vertisols (1%), Alfisols (13%), Mollisols (11%), Aridisols (0%), Spodosols (5%), and Ultisols (2%). This type of analysis is useful in identifying hotspots (e.g., soils with high fertility status; soils with the high social cost of carbon (SC-CO_2) emissions) [37,39].

Table 9. Soil diversity (pedodiversity) by soil order (taxonomic pedodiversity) within Land Resource Regions (LRRs) for the contiguous United States (U.S.) Soil Survey Geographic (SSURGO) Database (2020) [27].

LRRs	Slight <——— Degree of Weathering and Soil Development ———> Strong									
	Slight Weathering				Intermediate Weathering				Strong Weathering	
	Entisols	Inceptisols	Histosols	Andisols	Vertisols	Alfisols	Mollisols	Aridisols	Spodosols	Ultisols
	Area (km^2)									
A	5517	58,562	756	31,792	869	20,490	17,235	21	7706	15,577
B	10,114	2118	75	735	536	1123	96,455	38,224	0	0
C	27,378	14,900	450	14	9701	32,638	35,314	5891	0	396
D	253,840	30,096	225	3286	10,548	44,608	173,838	439,983	0	4121
E	29,371	102,155	724	27,487	1825	58,240	171,044	13,110	124	0
F	39,138	12,568	916	0	14,337	12,880	277,240	3636	0	0
G	192,349	45,344	79	0	23,681	37,585	122,002	88,697	0	0
H	64,551	51,798	0.21	124	9249	83,914	332,943	12,012	0	0
I	3636	13,797	0	0	11,528	28,910	88,233	23,691	0	0
J	6432	9976	0	0	29,024	63,995	31,348	0	0	1058
K	35,700	22,652	47,791	0	64	86,599	21,525	0	56,948	0
L	13,173	14,287	5281	0	0	52,200	12,324	0	8804	0
M	43,269	32,020	4659	0	3295	256,429	365,036	0	14	2538
N	18,594	103,952	23	0	331	163,582	20,069	0	654	250,411
O	9761	19,274	703	0	28,771	29,086	2822	0	0	411
P	53,392	53,155	2556	0	10,452	115,700	2295	0	1251	385,496
R	14,067	130,799	10,428	0	0	25,480	638	0	97,131	2070
S	5883	31,348	617	0	1.50	17,149	315	0	325	36,382
T	27,168	12,076	18,587	0	14,965	35,179	8497	329	18,182	70,396
U	19,185	2085	9491	0	11	12,344	3476	0	23,952	4079
Totals	**872,518**	**762,962**	**103,361**	**63,438**	**169,189**	**1,178,131**	**1,782,649**	**625,594**	**215,091**	**772,935**

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

For example, Mollisols have both high fertility status and a high potential for the social cost of carbon (SC-CO_2). Taxonomic pedodiversity within the boundaries of states and regions (Table 10) reveals that the states with the highest number of soil orders are: (1) Washington (11), (2) California and Oregon (10 each), and (3) Idaho and Montana (9 each). States with the highest number of soil series are: (1) California (2689), (2) Washington (1548), and (3) Idaho (1529). Table 11 provides a detailed distribution of various soil orders by state and region, with qualitative and quantitative assessments of soil stocks for ES/ED assessments. For example, for the state of Connecticut, the areas of soil orders are distributed as follows: Inceptisols (84%), Histosols (8%), Entisols (6%), and Mollisols (2%).

Table 10. Soil diversity (pedodiversity) expressed as the number of soil classes (taxonomic pedodiversity) within states (regions) in the contiguous United States (U.S.) based on Soil Survey Geographic (SSURGO) Database (2020) [27] with comparisons based on STATSGO (1997) [2].

State (Region)	Orders 2020 (1997)	Suborders	Great Groups	Subgroups	Series 2020 (1997)	Series Density 2020 (1997)
Connecticut	4	11	17	37	106 (86)	8.5 (6.7)
Delaware	6	13	23	46	70 (52)	13.9 (9.9)
Massachusetts	6 (5)	15	33	71	202 (129)	10.7 (6.2)
Maryland	7	19	47	105	287 (187)	11.4 (6.8)
Maine	5 (4)	16	36	79	231 (111)	2.9 (1.3)
New Hampshire	5 (4)	14	31	66	185 (127)	8.1 (5.3)
New Jersey	6 (7)	16	36	84	169 (148)	9.5 (7.5)
New York	7	25	64	168	823 (347)	6.9 (2.7)
Pennsylvania	7	17	46	109	391 (248)	3.4 (2.1)
Rhode Island	3	9	14	22	42 (45)	16.3 (15.9)
Vermont	6	18	39	102	231 (192)	9.7 (7.7)
West Virginia	7 (6)	17	40	88	250 (163)	4.1 (2.6)
(East)	**7**	**29**	**100**	**293**	**1763**	**3.5**
Iowa	6 (5)	35	17	118	486 (262)	3.4 (1.8)
Illinois	6	36	15	133	487 (358)	3.4 (2.5)
Indiana	7 (6)	35	16	126	451 (365)	4.8 (3.9)
Michigan	6	19	49	181	694 (371)	4.7 (2.5)
Minnesota	7 (6)	23	55	199	754 (620)	3.6 (2.8)
Missouri	6	18	41	142	403 (365)	2.3 (2.0)
Ohio	6	16	43	134	528 (339)	5.0 (3.2)
Wisconsin	7 (6)	19	48	176	663 (428)	4.7 (2.9)
(Midwest)	**8**	**30**	**93**	**403**	**3071**	**2.6**
Arkansas	6	18	47	129	397 (261)	2.9 (1.9)
Louisiana	7	15	39	115	253 (304)	2.3 (2.5)
Oklahoma	7	23	56	184	389 (463)	2.2 (2.6)
Texas	8	30	98	410	1512 (996)	2.3 (1.4)
(South Central)	**9**	**33**	**110**	**517**	**2249**	**2.1**
Alabama	8	19	48	127	365 (321)	2.8 (2.4)
Florida	8 (7)	22	49	150	340 (298)	2.5 (2.0)
Georgia	7	20	46	133	363 (250)	2.4 (1.6)
Kentucky	5 (6)	16	32	95	286 (211)	2.8 (2.0)
Mississippi	8 (7)	20	50	110	297 (220)	2.4 (1.8)
North Carolina	7 (6)	20	43	116	355 (228)	2.8 (1.8)
South Carolina	7	18	39	105	232 (214)	3.0 (2.7)
Tennessee	7 (6)	19	43	135	621 (344)	6.0 (3.2)
Virginia	8 (7)	20	54	129	529 (265)	5.2 (2.5)
(Southeast)	**8**	**27**	**87**	**371**	**2169**	**2.1**
Colorado	8	35	93	347	1292 (856)	5.1 (3.2)
Kansas	7	23	55	168	473 (370)	2.2 (1.7)
Montana	9	44	128	464	1465 (693)	4.2 (1.8)
North Dakota	6 (7)	20	43	128	282 (272)	1.6 (1.5)
Nebraska	7 (6)	21	44	131	428 (268)	2.2 (1.3)
South Dakota	7 (6)	28	72	225	751 (563)	3.9 (2.8)
Wyoming	8 (7)	40	108	403	1448 (794)	6.3 (3.1)
(Northern Plains)	**11**	**53**	**173**	**811**	**4619**	**2.9**
Arizona	7 (6)	26	68	222	915 (423)	3.4 (1.4)
California	10	52	161	597	2689 (1755)	7.6 (4.3)
Idaho	9	45	131	454	1529 (1083)	7.8 (5.0)
New Mexico	8 (7)	31	88	299	1174 (744)	4.1 (2.4)
Nevada	8	33	88	378	1361 (1354)	5.1 (4.7)
Oregon	10	47	139	462	1481 (1075)	6.2 (4.3)
Utah	8 (7)	35	95	369	1415 (1006)	7.6 (4.6)
Washington	11 (9)	45	132	438	1548 (912)	9.6 (5.1)
(West)	**11**	**63**	**260**	**1421**	**9375**	**4.8**
Totals	**11**	**65**	**317**	**2026**	**19,602**	**2.7**

Note: Series density equals the number of series divided by 100,000 ha.

Table 11. Soil diversity (pedodiversity) by soil order (taxonomic pedodiversity) in the contiguous United States (U.S.) based on Soil Survey Geographic (SSURGO) Database (2020) [27].

State (Region)	Slight <——— Degree of Weathering and Soil Development ———> Strong									
	Slight Weathering				Intermediate Weathering				Strong Weathering	
	Enti-sols	Incepti-sols	Histo-sols	Andi-sols	Verti-sols	Alfi-sols	Molli-sols	Aridi-sols	Spodo-sols	Ulti-sols
	Area (km^2)									
Connecticut	784	10,374	1052	0	0	0	196	0	0	0
Delaware	1072	125	121	0	0	59	0	0	27	3639
Massachusetts	3832	11,552	1542	0	0	0	3	0	1977	13
Maryland	2162	3254	591	0	0	2602	34	0	47	16,576
Maine	1099	21,286	6286	0	0	0	18	0	51,895	0
New Hampshire	1206	8697	1617	0	0	0	3	0	11,277	0
New Jersey	3587	3180	724	0	0	1734	0	0	1484	7078
New York	7238	63,843	3518	0	0	20,233	856	0	22,167	576
Pennsylvania	4200	44,708	223	0	0	24,961	138	0	203	40,858
Rhode Island	489	2036	58	0	0	0	0	0	0	0
Vermont	905	9265	395	0	0	1010	137	0	12,053	0
West Virginia	4257	18,871	33	0	0	13,980	122	0	482	23,702
(East)	**29,768**	**197,828**	**13,844**	**0**	**0**	**63,022**	**1119**	**0**	**106,720**	**92,025**
Iowa	9611	12,070	152	0	295	34,439	87,234	0	0	0
Illinois	12,239	4947	380	0	0	61,155	65,121	0	0	107
Indiana	6276	9429	1301	0	0	51,962	21,045	0	3	3568
Michigan	18,137	12,051	13,295	0	0	44,231	12,865	0	46,952	0
Minnesota	16,942	20,714	28,759	0	4387	44,288	93,878	0	254	0
Missouri	8837	5657	0	0	2759	91,360	40,204	0	0	28,667
Ohio	5739	13,700	406	0	0	66,356	12,555	0	0	6685
Wisconsin	16,878	4976	14,587	0	0	63,450	15,799	0	24,849	2
(Midwest)	**93,424**	**78,531**	**60,744**	**0**	**6866**	**477,096**	**337,608**	**0**	**68,509**	**38,778**
Arkansas	7324	13,765	0	0	7097	35,779	3745	0	0	68,121
Louisiana	8525	12,317	7165	0	15,743	41,476	1168	0	0	22,879
Oklahoma	17,904	21,679	0	0	6501	45,022	71,197	266	0	14,078
Texas	41,454	64,235	0	0	61,723	170,569	218,194	79,732	15	24,727
(South Central)	**70,892**	**105,988**	**8092**	**0**	**95,568**	**297,126**	**296,443**	**75,817**	**10**	**132,467**
Alabama	21,800	20,410	1084	0	3168	7298	1296	0	19	75,872
Florida	35,568	5929	12,643	0	13	15,803	5477	0	33,349	27,708
Georgia	14,331	10,028	1582	0	0	3408	3	0	3286	116,647
Kentucky	3021	26,852	0	0	0	44,876	3233	0	0	23,865
Mississippi	21,348	18,906	761	0	8967	30,808	478	0	1	41,313
North Carolina	8450	25,796	4882	0	0	6675	363	0	2736	76,622
South Carolina	6663	8167	462	0	0	7287	232	0	1156	54,521
Tennessee	7234	21,321	0	0	100	28,366	4600	0	0	42,657
Virginia	5445	20,589	817	0	23	10,560	645	0	28	64,607
(Southeast)	**98,026**	**139,879**	**24,312**	**0**	**13,943**	**164,043**	**14,144**	**0**	**46,166**	**551,642**
Colorado	53,635	17,712	397	0	1824	41,700	91,424	47,089	107	0
Kansas	16,343	5552	0	0	9457	11,254	169,487	156	0	76
Montana	70,088	89,506	486	8600	11,800	41,922	115,914	12,518	5	0
North Dakota	13,271	7352	20	0	6962	832	150,151	0	0	0
Nebraska	92,172	5574	22	0	620	3165	96,746	119	0	0
South Dakota	30,742	9172	13	0	16,518	5851	126,070	3549	0	0
Wyoming	69,454	23,384	253	356	639	24,678	55,786	54,725	0	0
(Northern Plains)	**343,944**	**154,780**	**726**	**1551**	**42,374**	**121,581**	**836,422**	**113,683**	**112**	**75**
Arizona	88,659	2472	4	0	3483	11,706	33,412	127,130	0	0
California	83,218	64,545	734	2928	15,945	69,846	81,653	25,034	47	10,023
Idaho	9126	34,112	176	19,004	1111	12,205	77,220	44,184	0	17
New Mexico	63,846	8102	10	86	1898	32,215	61,969	11,6232	0	0
Nevada	74,116	5633	4	165	870	1306	62,434	12,4888	0	0
Oregon	5819	52,931	521	25,895	2265	14,876	95,277	29,023	692	12,577
Utah	68,382	5582	7	7	440	2700	47,003	60,909	0	0
Washington	9542	31,326	872	37,798	47	6443	53,974	9927	8847	3093
(West)	**369,521**	**174,653**	**2229**	**83,077**	**26,562**	**156,171**	**516,161**	**593,340**	**10,273**	**26,557**
Totals	**982,571**	**859,445**	**116,378**	**72,379**	**190,455**	**1326,421**	**2009,454**	**704,900**	**242,181**	**870,043**

Note: Soil order of Gelisols was reported for the state of Washington with an area of 11 m^2.

3.1.2. Examples of Genetic Pedodiversity and Ecosystem Services

Genetic pedodiversity refers to the diversity of genetic horizons (soil layers commonly parallel to the soil surface), which designation indicates a qualitative description of changes) (Figure 3, Table 12) [15,40]. Diagnostic horizons are quantitatively defined and not equivalent to the genetic horizons in Soil Taxonomy [15]. Soil horizons are integral components of the taxonomic pedodiversity and can be used to compute distinct or combined stocks within the soil (Figure 3, Table 12).

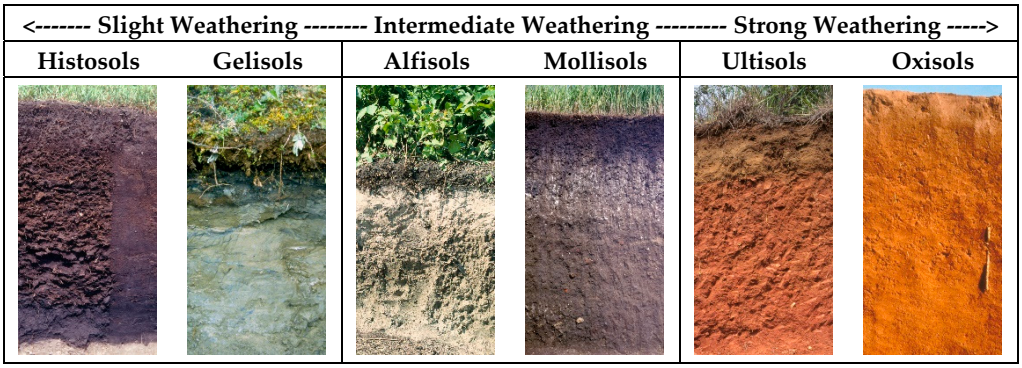

Figure 3. Examples of variations of soil horizons in different soil profiles.

Table 12. Examples of soil profile horizons (master horizons and corresponding lowercase letters commonly used with these horizons) and ecosystem services (adapted from Hartemink et al. (2020) [40].

Soil Profile Horizons		Ecosystem Services		
Master Horizons (Lowercase Letters)	**Description**	**Provisioning**	**Regulation and Maintenance**	**Cultural**
O	**Horizon with organic matter and plant litter**	x	x	ND
i	Slightly decomposed organic matter (fibric)	x	x	ND
e	Intermediately decomposed organic matter (hemic)	x	x	ND
a	Highly decomposed organic matter (sapric)	x	x	ND
A	**Zone of organic matter accumulation in the soil**	x	x	ND
p	Plowing or other disturbance	x	x	ND
E	**Zone of maximum eluviation**	x	x	ND
B	**Zone of maximum illuviation**	x	x	ND
c	Concretions or nodules	x	x	ND
b	Buried	x	x	ND
f	Frozen (permafrost)	x	x	ND
g	Strong gleying (mottling)	x	x	ND
h	Illuvial accumulation of organic matter (OM)	x	x	ND
j	Jarosite (yellow sulfur mineral)	x	x	ND
jj	Cryoturbation (frost churning)	x	x	ND
k	Accumulation of carbonate ($CaCO_3$)	x	x	ND
m	Cementation or induration	x	x	ND
n	Accumulation of sodium	x	x	ND
o	Accumulation of Fe and Al oxides	x	x	ND
q	Accumulation of silica	x	x	ND
s	Illuvial accumulation of OM and Fe and Al oxides	x	x	ND
ss	Slikenslides (shiny clay wedges)	x	x	ND
t	Accumulation of silicate clays	x	x	ND
v	Plinthite (high iron, red material)	x	x	ND
w	Distinctive color or structure	x	x	ND
x	Fragipan (high bulk density, brittle)	x	x	ND
y	Accumulation of gypsum ($CaSO_4 \cdot 2H_2O$)	x	x	ND
z	Accumulation of soluble salts	x	x	ND
C	**Weathered or soft rock**	x	x	ND
R	**Bedrock, consolidated rock**	x	x	ND

Note: ND = not determined. "True soil" = A, E, B. Regolith (weathered material) = O, A, E, B, C. Contributions of the different soil horizons to ES will vary with soil order, geographic location, environmental conditions, anthropologic setting, etc.

Numerous combinations of master horizons and their lowercase letters describe the incredible diversity of soil resources in the landscape. Soil horizons vary in thickness and exhibit within-horizon lateral and vertical variation [40]. Although all of the horizons in Table 12 present various types of value (e.g., market and non-market), some of these horizons can be over-exploited for their ES. For example, horizon A is commonly plowed for agricultural production and subject to nutrient depletion and erosion [41]. Ireland had to pass policies to protect peatlands, which often contain soil order of Histosols with horizon O in various stages of decomposition (lowercase letters: i, e, a, Table 12), which is used for multiple purposes (e.g., fuel and horticulture) [42]. Permafrost (indicated by the lowercase letter f in Table 12) is thawing rapidly, releasing large amounts of carbon dioxide and methane gases [43].

3.1.3. Examples of Parametric Pedodiversity and Ecosystem Services

Parametric pedodiversity refers to the diversity of soil properties, which are also often used in the context of taxonomic and genetic pedodiversities. Soil properties vary by soil type and exhibit within-horizon lateral and vertical variation [40]. Although there is no standardized list of soil properties, Adhikari and Hartemink (2016) [16] provided key soil properties related to ES: soil organic carbon; sand, silt, clay, and coarse fragments; pH; depth to bedrock; bulk density; available water capacity; cation exchange capacity; electrical conductivity; soil porosity and air permeability; hydraulic conductivity and infiltration; soil biota; soil structure and aggregation; soil temperature; clay mineralogy, and subsoil pans. This list seems to focus primarily on soil physical properties, but soil chemical properties and qualitative soil descriptions (e.g., official soil series descriptions) are also important in ES/ED valuations. Soil chemical properties (e.g., plant nutrients) are essential for agricultural production, and it is important to monitor the supply of these nutrients to meet the yearly recommended dietary allowances and intakes by population [44]. For example, Zurqani et al. (2019) [45] quantified the yearly human demand for major and trace elements in Libya by different administrative units with the future goal of linking it with the provisioning ES supply by the country's soils.

Very often, soil properties serve multiple ES/ED. For example, Groshans et al. (2018) [30] determined the provisioning value of soil inorganic carbon (SIC) based on liming replacement cost within the contiguous U.S. However, SIC can also be valued as a regulating ES/ED, and Groshans et al. (2019) [46] estimated the value of SIC stocks based on the avoided social cost of carbon emissions (SC-CO_2). There are numerous challenges in using appropriate soil data sources and valuation methods for soil properties. For example, Mikhailova et al. (2019) [47] compared field sampling and soil survey database for spatial heterogeneity in surface granulometry (sand, silt, and clay) for potential use in ES/ED valuations and concluded that field sampling provided more detailed information. The same study revealed that soil texture and coarse fragments are lithospheric-derived resources (Figure 1) and can be valued based on "soil" or "mineral" stock. Among soil properties, soil organic matter (SOM) and soil organic carbon (SOC) are the most researched soil properties because of their significance in provisioning (e.g., soil fertility) and regulating (e.g., carbon sequestration) ES. Guo et al. (2006) [39] reported spatial variability of soil carbon (SOC, SIC) in each of the soil orders within the contiguous U.S., and potential decline in SOC in the 0–20 cm depth (e.g., rooting depth of most crops) compared to 20–100 cm depth. Taxonomic pedodiversity and human demand for soil nutrients can adversely affect soil health and nutritional security [48].

3.1.4. Examples of Functional Pedodiversity and Ecosystem Services

Functional pedodiversity refers to soil behavior under different uses. Taxonomic and genetic pedodiversities influence soil behavior under current and potential uses. According to Amundson et al. (2003) [2], "in less than two centuries, the landscape of the U.S. has been transformed to the degree that would astound our 19th-century predecessors". According to Merrill and Leatherby (2018) [49], "the 48 contiguous states alone are

1.9 billion-acre jigsaw puzzle of cities, farms, forests and pastures that Americans use to feed themselves, power their economy and extract value for business and pleasure" with six major types of land: cropland (391.5M acres, where M = million = 10^6), forest (538.6M acres), pasture/range (654M acres), urban (69.4M acres), special use (168.6M acres), and miscellaneous (68.9M acres). Soils under different uses make a significant contribution to various ES/ED in the contiguous U.S., but monetary valuations of these ES/ED are rare at this scale. For example, Groshans et al. (2018) [46] assessed the value of SIC for provisioning ES for LRRs based on liming replacement cost (a 2014 U.S. average price of $10.42 per U.S. ton of agricultural limestone). The LRRs with the highest midpoint total replacement cost value of SIC storage were: (1) D—Western Range and Irrigated Region ($1.10T), (2) H—Central Great Plains Winter Wheat and Range Region ($926B), and (3) M—Central Feed Grains and Livestock Region ($635B) [46]. On an area basis, the highest replacement cost values were: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($3.33 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region ($2.83 m^{-2}), and (3) H—Central Great Plains Winter Wheat and Range Region ($1.59 m^{-2}) [46]. The LRRs with the highest mean replacement cost values per area over the depth interval 0–20 cm were: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($0.43 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region ($0.27 m^{-2}) and (3) D—Western Range and Irrigated Region ($0.11 m^{-2}) [46]. Over the depth interval 0–100 cm, the highest mean replacement cost values were: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($1.86 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region ($1.49 m^{-2}) and (3) F—Northern Great Plains Spring Wheat Region ($0.70 m^{-2}) [46].

Traditionally, provisioning ES have been seen as the primary value from the soil; however, in the face of potentially severe economic impacts from climate change, regulating ES should be recognized for their potential to provide ES through mitigation of net CO_2 release through different management regimes designed to maximize CO_2 uptake and minimize CO_2 release. Site-specific management of soil carbon "hotspots" through precision agriculture could serve to reduce CO_2 emission and provide regulating ES to humanity [37]. Although no economic system has been developed to coordinate long-term practices to sequester C [50], any contribution to CO_2 reduction would help mitigate emissions from fossil fuels. Different soil carbon (SOC, SIC, and TSC) should be accounted for in the mitigation efforts. A few studies attempted to put a monetary value on regulating ES/ED from SOC, SIC, and TSC within the contiguous U.S. using the social cost of carbon (SC–CO_2) of $42 per metric ton of CO_2, which is applicable for the year 2020 based on 2007 U.S. dollars and an average discount rate of 3% [35,36,46,51]. According to Mikhailova et al. (2019) [36], the LRRs with the highest TSC storage value (based on the avoided social cost of carbon emissions) were: (1) M—Central Feed Grains and Livestock Region ($2.82T), (2) D—Western Range and Irrigated Region ($2.64T), and (3) H—Central Great Plains Winter Wheat and Range Region ($2.48T). The value of TSC based on area density within LRR boundaries were ranked: (1) I—Southwest Plateaus and Plains Range and Cotton Region ($6.90 m^{-2}), (2) J—Southwestern Prairies Cotton and Forage Region ($6.38 m^{-2}), and (3) U—Florida Subtropical Fruit, Truck Crop and Range Region ($6.25 m^{-2}) [36].

3.2. Extrinsic Factors: Examples of Monetary Valuations Based on Interaction of Soil Diversity (Pedodiversity) and the Earth's Spheres

Pedodiversity is influenced by extrinsic (outside soil) factors from atmosphere, biosphere, hydrosphere, lithosphere, ecosphere, and anthroposphere (Figure 1), which can increase or decrease the value of ES/ED associated with pedodiversity. Valuations of both intrinsic and extrinsic factors can be made within biophysical accounts (e.g., within soil order boundaries) and then "translated" into the administrative accounts for decision making. For example, Figure 4 demonstrates the share between values of total soil carbon (intrinsic) and average annual total (extrinsic) monetary values of non-constrained potential soil inorganic carbon (SIC) sequestration from combined atmospheric Ca^{2+} and Mg^{2+} deposition (2000–2015) for different regions in the contiguous U.S. based on an avoided SC–CO_2 of $42 per metric ton of CO_2. In this case, both intrinsic (TSC) and extrinsic (poten-

tial for SIC sequestration from atmospheric Ca^{2+} and Mg^{2+} deposition) factors are spatially heterogeneous without considering physical and economic constraints for achieving the maximum potential for SIC sequestration from atmospheric sources [52]. Both intrinsic and extrinsic factors limit pedodiversity in its ability to supply ES/ED.

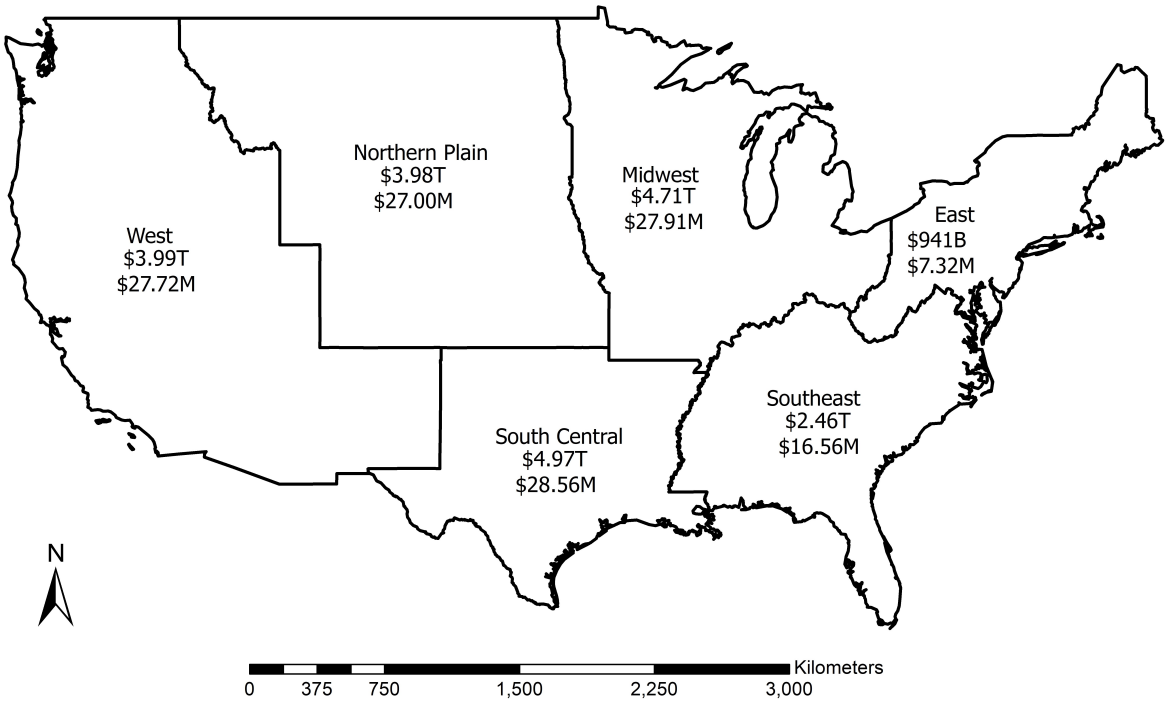

Figure 4. Total soil carbon **(intrinsic, top number**) and average annual total **(extrinsic, bottom number)** monetary values of non-constrained potential soil inorganic carbon (SIC) sequestration from combined atmospheric Ca^{2+} and Mg^{2+} deposition (2000–2015) for different regions in the contiguous United States (U.S.) based on an avoided SC–CO_2 of $42 per metric ton of CO_2 [51] (adapted from Mikhailova et al., 2019 [36]; Mikhailova et al., 2020 [52]). Note: M = million = 10^6, B = billion = 10^9, and T = trillion = 10^{12}.

Climate change is another set of extrinsic factors impacting the value of ES/ED derived from pedodiversity. Global warming threatens the existence of soil order of Gelisols because of thawing permafrost. Gelisols store large amounts of soil organic matter (SOM), and its decomposition can release large amounts of carbon dioxide and methane [53]. An increase in both ambient and soil temperature can intensify SOM decomposition and lead to self-ignition conditions in soil carbon-rich soils (e.g., Gelisols, Histosols), leading to wildfires [54]. Climate change is also predicted to increase global water erosion from 30 to 66% [55].

Urbanization, another example of extrinsic factors, alters soils in various ways (e.g., erosion and pollution) and creates ES/ED specific to urban soil diversity (urban pedodiversity), which requires adjustment of valuations to urban environments [56,57]. Urbanization alters the stocks and flows of ES/ED provided by soils in urban and non-urban environments since urban environments are not self-supporting, which creates a significant demand for ES from urban fringes and beyond [58].

3.3. Pedodiversity Threats and Losses in the Contiguous U.S. in Relation to Ecosystem Services

3.3.1. Land Cover Change (LCC) as a Threat to Pedodiversity

Pedodiversity in the contiguous U.S. is experiencing significant threats and losses, especially in agriculturally productive and important soils (e.g., Alfisols and Mollisols) and regions (e.g., Midwest, Northern Plains, South Central) that is driven by land cover change (e.g., urbanization, deforestation, and agricultural expansion) [2]. These soils and regions

have high provisioning ES value, which can result in unsustainable use accompanied by the loss of regulating and provisioning ES services [59]. Although the economic value of ES from agriculturally productive soils is somewhat reflected in the total value of U.S. agricultural production, the social costs associated with this production and rates of soil diversity (pedodiversity) extinction are rarely reported (Table 13) [2]. The total social costs of agricultural production (present and past) are difficult to quantify because they are impacted by numerous factors, but on-going research on ES/ED provides useful insight into potential valuation methods. This type of analysis should account for ES and ED (actual or realized, and potential) provided by pedodiveristy using biophysical (e.g., soil orders) and administrative (e.g., states) accounts. For example, Groshans et al. (2018) [30,59] assessed the midpoint total provisioning value of SIC for ES for Mollisols in the contiguous U.S. based on liming replacement costs (average price of limestone in 2014, \$10.42 per U.S. ton) in 2 m soil depth at \$23.2B, USD (where B = billion = 10^9). A follow-up study estimated the regulating value of SIC for ES/ED for Mollisols in the contiguous U.S. based on a social cost of carbon (SC-CO_2) of \$42 U.S. dollars and reported a total midpoint value of \$3.57T, USD (where T = trillion = 10^{12}) [48].

Soil organic carbon is particularly important for agricultural production, and Mikhailova et al. (2019) [35] estimated the value of SOC stocks in the contiguous United States based on the avoided social costs of carbon emissions and reported that the total calculated monetary value for SOC storage in the contiguous U.S. was between \$4.64T and \$23.1T, with a midpoint value of \$12.7T [35]. Soil orders with the highest midpoint SOC storage values were (1): Mollisols (\$4.21T), (2) Histosols (\$2.31T), and (3) Alfisols (\$1.48T) [35]. The midpoint values of SOC normalized by area within soil order boundaries were ranked: (1) Histosols (\$21.58 m^{-2}), (2) Vertisols (\$2.26 m^{-2}), and (3) Mollisols (\$2.08 m^{-2}) [35]. States with the highest midpoint values of SOC storage were: (1) Texas (\$1.08T), (2) Minnesota (\$834B), and (3) Florida (\$742B) [35]. Midpoint values of SOC normalized by area within state boundaries were ranked: (1) Florida (\$5.44 m^{-2}), (2) Delaware (\$4.10 m^{-2}), and (3) Minnesota (\$3.99 m^{-2}) [35]. Regions with the highest midpoint values of SOC storage were: (1) Midwest (\$3.17T), (2) Southeast (\$2.44T), and (3) Northern Plains (\$2.35T) [35]. Midpoint values of SOC normalized by area within region boundaries were ranked: (1) Midwest (\$2.73 m^{-2}), (2) Southeast (\$2.31 m^{-2}), and (3) East (\$1.82 m^{-2}) [35].

Mapping can provide spatial context between population, urbanization, and endangered soil series (Table 13, Figures 5 and 6). Results show that there is a link between states and regions with a high number of endangered soil series and the value of provisioning and regulating ES (California; Midwest, Northern Plains, and South-Central regions). States and regions with zero endangered series represent areas with generally low productivity soils such as Aridisols (e.g., Arizona and New Mexico), Ultisols (e.g., Georgia, South Carolina, and North Carolina), and Entisols and Inceptisols (e.g., Maine and Vermont) (Table 13, Figure 5).

Some states and regions have low human populations, but some of the highest proportions of endangered rare soil series (Table 13, Figure 5). For example, the Northern Plains region has only 4.19% of the total U.S. population and some of the highest numbers of endangered soil series [60,61]. In the Midwest, Iowa has almost 81% of its rare soil series endangered, but it has only 0.95% of the total U.S. population (Table 13, Figure 5) [60,61]. Similarly, Kansas has nearly 43% of its rare soil series endangered, but it has only 0.88% of the U.S. population. These states have some of the highest values associated with provisioning ES from SOC, SIC, and TSC, as well as regulating ES/ED associated with these carbon stocks. A mismatch between "potential" and "realized" supply/demand of flow-dependent ES/ED [62] is not a new phenomenon for Kansas, which experienced soil

Table 13. Pedodiversity and selected population statistics in the contiguous United States (U.S.) (adapted from Amundson et al., 2003 [2], and Wikipedia [60]).

State (Region)	Orders	Series	Rare Series	Endangered Series	% of Rare Series Endangered	Extinct Soil Series	Percent of the Total U.S. Population (2019)	Percent Urban Population within State (2010)
Connecticut	4	86	8	4	50.0		1.07	88.0
Delaware	6	52	0	0	0.0		0.29	83.3
Massachusetts	5	129	5	0	0.0		2.09	92.0
Maryland	7	187	7	0	0.0		1.82	87.2
Maine	4	111	8	0	0.0		0.41	38.7
New Hampshire	4	127	10	0	0.0		0.41	60.3
New Jersey	7	148	22	2	9.1		2.68	94.7
New York	7	347	37	2	5.4		5.86	87.9
Pennsylvania	7	248	20	0	0.0		3.86	78.7
Rhode Island	3	45	2	0	0.0		0.32	90.7
Vermont	6	192	24	0	0.0		0.19	38.9
West Virginia	6	163	11	0	0.0		0.54	48.7
(East)	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**19.54**	**n/a**
Iowa	5	262	26	21	80.8		0.95	64.0
Illinois	6	358	44	29	65.9	6	3.82	88.5
Indiana	6	365	44	36	81.8	2	2.03	72.4
Michigan	6	371	86	10	11.6		3.01	74.6
Minnesota	6	620	122	65	53.3	6	1.70	73.3
Missouri	6	365	27	12	44.4	4	1.85	70.4
Ohio	6	339	46	21	45.7	2	3.52	77.9
Wisconsin	6	428	51	8	15.7		1.75	70.2
(Midwest)	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**18.63**	**n/a**
Arkansas	6	261	3	1	33.3		0.91	56.2
Louisiana	7	304	41	10	24.4	1	1.40	73.2
Oklahoma	7	463	46	3	6.5		1.19	66.2
Texas	8	996	176	6	3.4		8.74	84.7
(South Central)	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**12.24**	**n/a**
Alabama	8	321	19	0	0.0		1.48	59.0
Florida	7	298	67	9	13.4	3	6.47	91.2
Georgia	7	250	4	0	0.0		3.20	75.1
Kentucky	6	211	14	0	0.0		1.35	58.4
Mississippi	7	220	17	2	11.8		0.90	49.3
North Carolina	6	228	18	0	0.0		3.16	66.1
South Carolina	7	214	13	0	0.0		1.55	66.3
Tennessee	6	344	44	3	6.8		2.06	66.4
Virginia	7	265	10	0	0.0		2.57	75.5
(Southeast)	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**22.74**	**n/a**
Colorado	8	856	153	0	0.0		1.74	86.2
Kansas	7	370	14	6	42.9		0.88	74.2
Montana	9	693	188	21	11.2		0.32	55.9
North Dakota	7	272	26	10	38.5		0.23	59.9
Nebraska	6	268	23	14	60.9	2	0.58	73.1
South Dakota	6	563	61	18	29.5		0.27	56.7
Wyoming	7	794	121	0	0.0		0.17	64.8
(Northern Plains)	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**4.19**	**n/a**
Arizona	6	423	27	0	0.0		2.19	89.9
California	10	1755	671	104	15.5	1	11.9	95.0
Idaho	9	1083	361	49	13.6		0.54	70.6
New Mexico	7	744	139	0	0.0		0.63	77.4
Nevada	8	1354	399	1	0.3		0.93	94.2
Oregon	10	1075	301	16	5.3		1.27	81.0
Utah	7	1006	279	5	1.8		0.97	90.6
Washington	9	912	462	25	5.4	3	2.29	84.0
(West)	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**20.72**	**n/a**
Totals	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**98.06**	**80.7**

Note: n/a = not available. For "series abundance," the following categories are defined [2]: (a) rare soils—less than 1000 ha total area in the US, and (b) endangered soils as those rare or rare-unique soil series that have lost more than 50% of their area to various land disturbances.

degradation and the Dust Bowl in the past due to a combination of prolonged drought and "suitcase farming," which was sponsored by "non-resident farmers" [63]. From the ES framework perspective, examining the potential for dry land farming in the 1920s, it would have indicated limitations due to intrinsic factors (high soil erodibility because of silty soil texture) and extrinsic factors (susceptibility of this area to regular droughts). According to Lee and Gill [64], the soil and drought conditions were compounded by an economic collapse that reduced crop value. Social costs associated with the Dust Bowl went far beyond the boundaries of the states where it originated, with almost half a million Dust Bowl refugees, massive quantities of topsoil being deposited in the Atlantic Ocean and impacting the air quality of Washington D.C. and other faraway states [64]. The ES framework, in combination with detailed spatial and temporal environmental data, can be used to inform sustainable decision-making to help avoid and mitigate similar and other disasters.

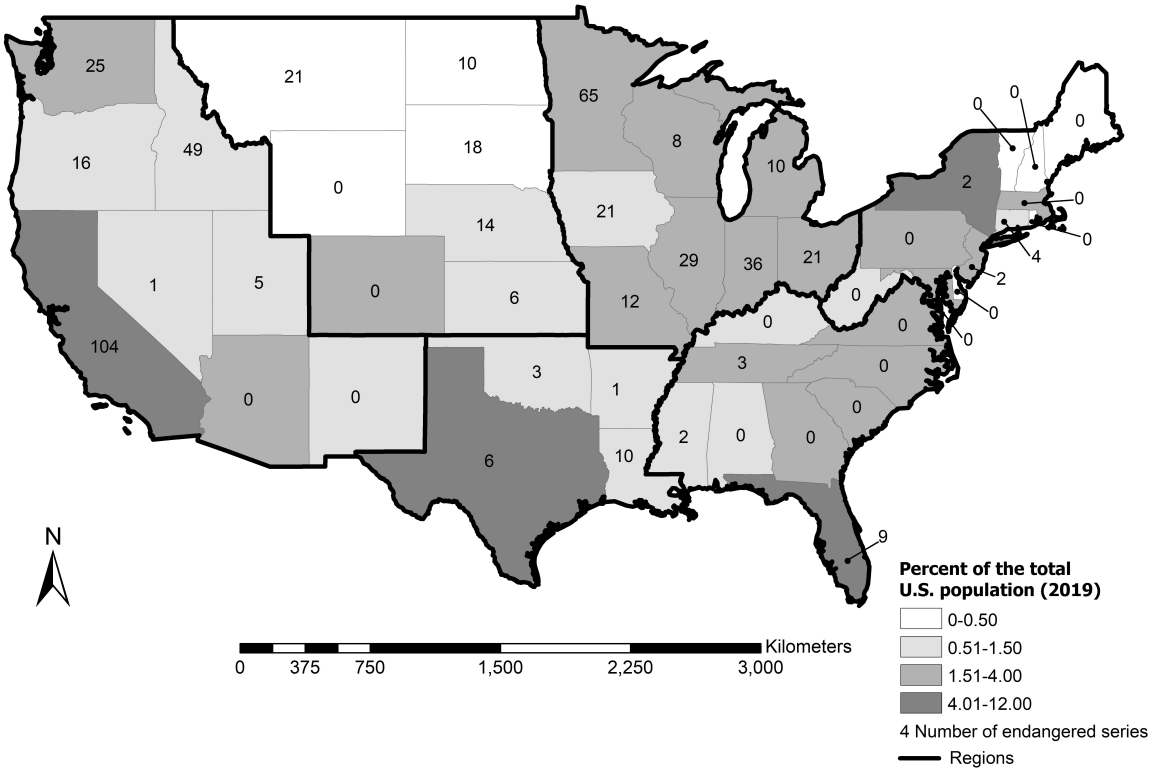

Figure 5. Number of endangered soil series [2] and percent of the total U.S. population (2019) [60] in the contiguous United States (U.S.).

For example, land cover change maps over time can provide insight into geographical patterns of ES stocks, flows, and values. Urbanization trends increase demand for ES, which are not always supplied by local soil resources and require soil ecosystem goods and services to be "imported" from soil stocks in other geographic areas (Figures 6 and 7). Figure 7 shows large urban area increases in the states of Texas, California, Florida, Arizona, Georgia, and North Carolina. Increases in urban areas in states can be accompanied by decrease in the agricultural areas (e.g., Florida, Arizona, and Georgia) and/or loss of forest areas (e.g., California, Arizona, Texas, and Georgia) (Figures 8 and 9).

In some cases, states increase the flow of ecosystem goods and services by increasing the agricultural area within the state based on available soil resources (e.g., Texas) (Figure 8). In other cases, an increase in the flow of ecosystem goods and services by increasing the agricultural area may be limited because of constraints associated with inherently low-fertility soils and other extrinsic factors (e.g., low precipitation).

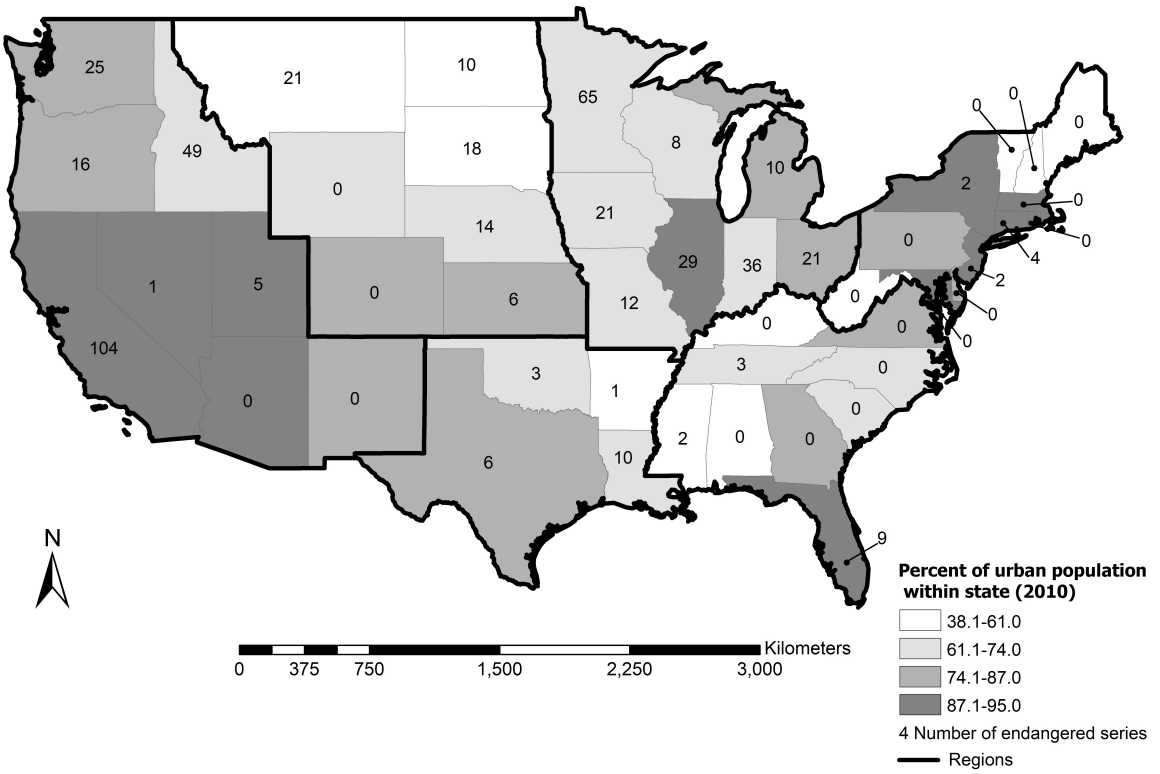

Figure 6. Number of endangered soil series [2] and percent of the urban population within each state (2010) [61] in the contiguous United States (U.S.).

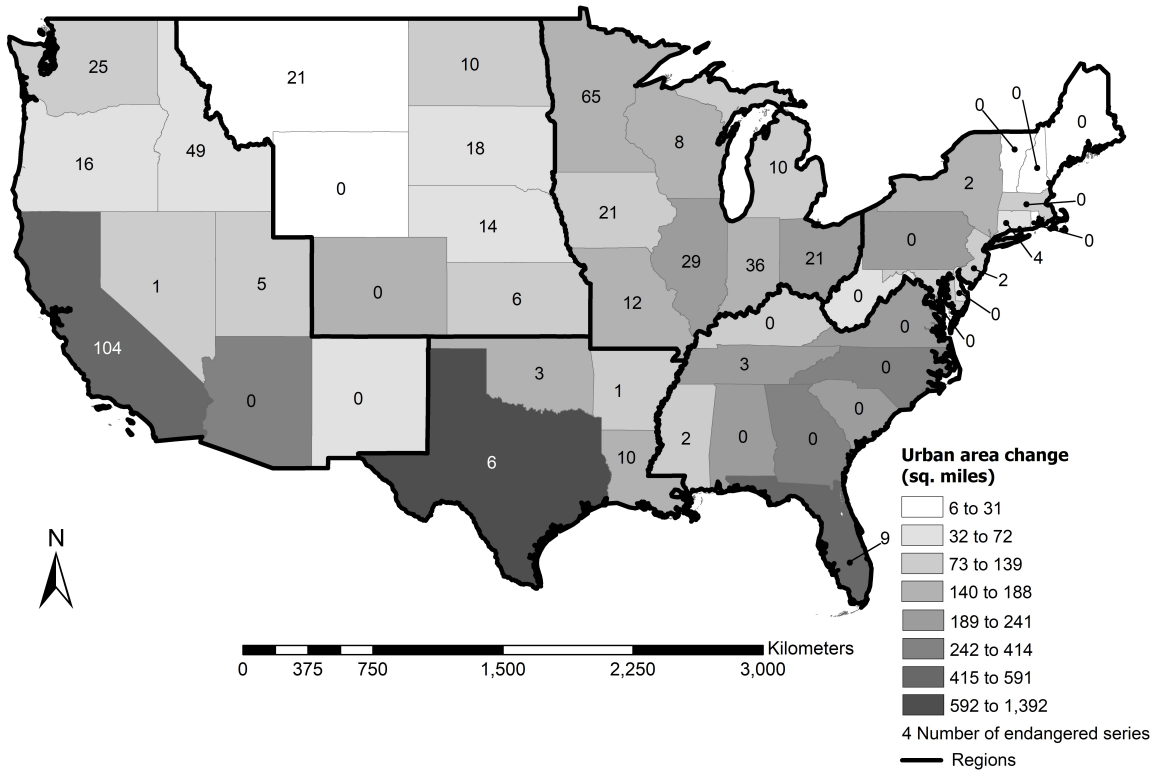

Figure 7. Urban land cover changes over time from 2001 to 2011 in the contiguous United States (U.S.) (adapted from Wentland et al. (2020) [65]).

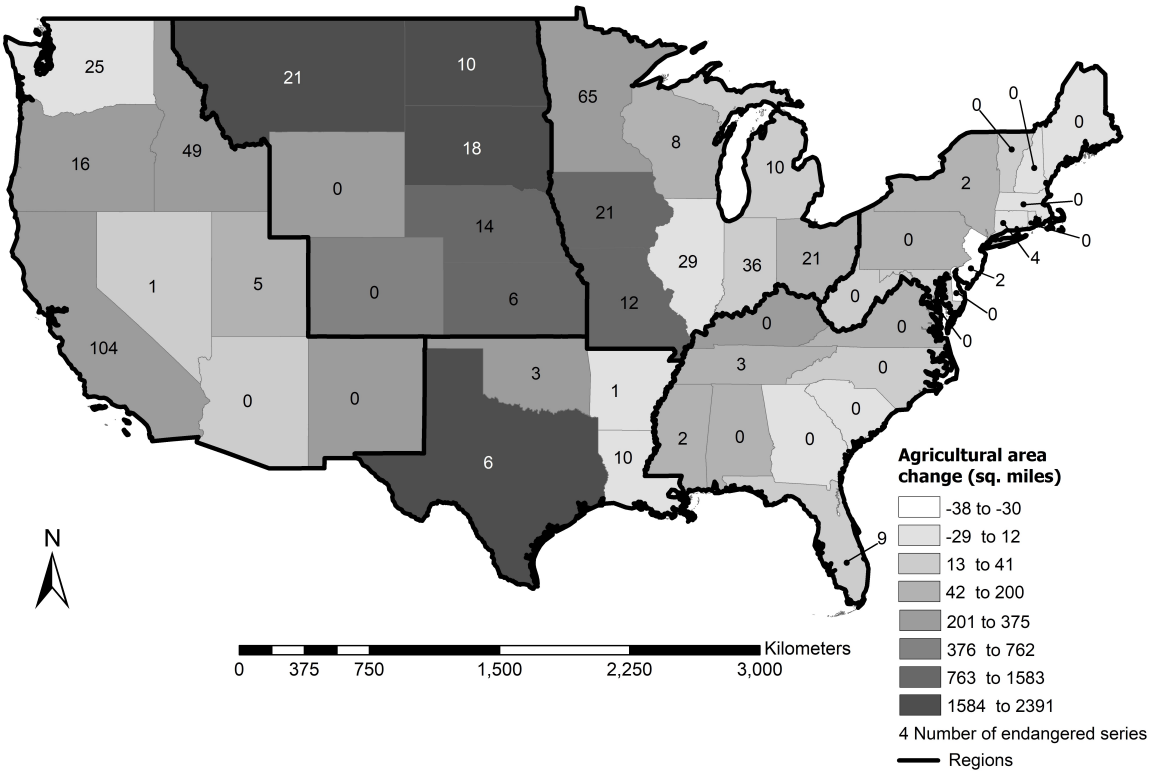

Figure 8. Agricultural land cover changes over time from 2001 to 2011 in the contiguous United States (U.S.) (adapted from Wentland et al. (2020) [65]).

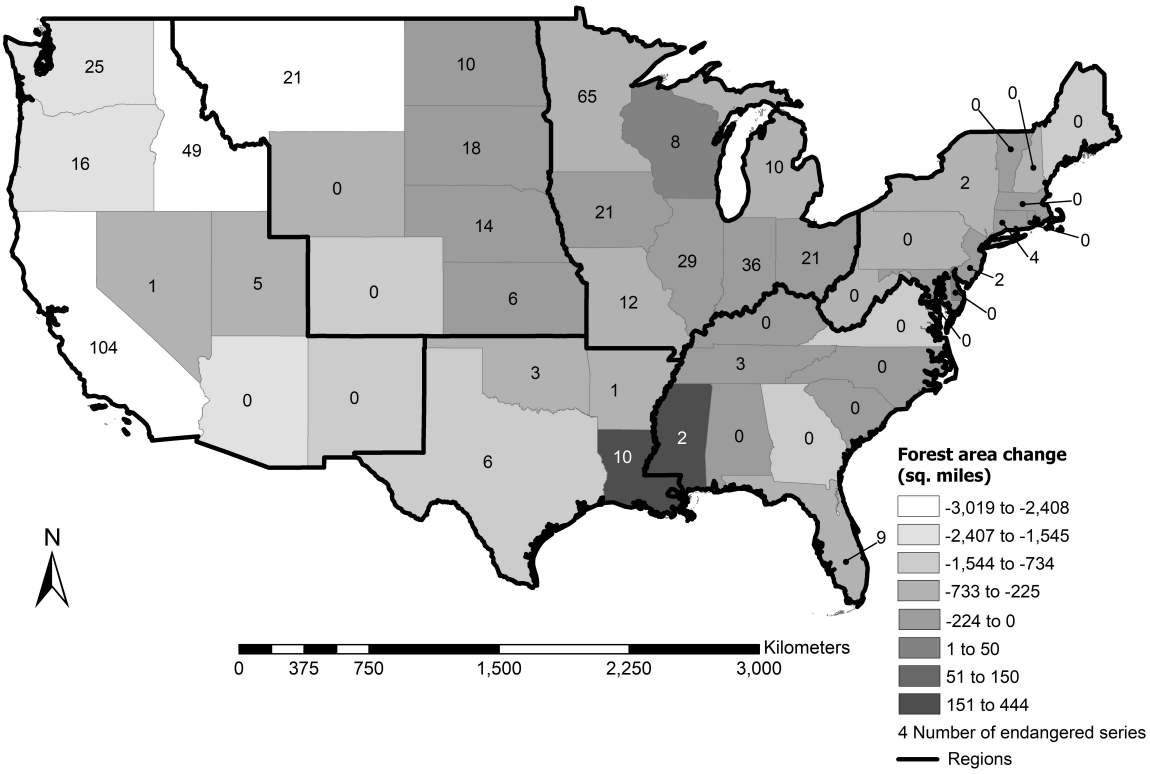

Figure 9. Forest land cover changes over time from 2001 to 2011 in the contiguous United States (U.S.) (adapted from Wentland et al. (2020) [65]).

According to Wentland et al. (2020) [65], overall U.S. land cover has seen declines in agricultural areas, forests, and pasture, and increases in developed areas as well as barren, and scrub/shrub land cover classes. These declines are mostly concentrated in the Southeastern U.S. [65].

Land cover and its change are important in ES valuations. Wetland et al. (2020) [65] estimated the total value of private land in the contiguous United States at $25.1T (T = trillion = 10^{12}) in 2016 using the Zillow Transaction and Assessment Dataset, which includes individual property attributes linked to market transaction price data. These values do not necessarily represent ES values (intrinsic and extrinsic) because there are no available tools for the public to appraise any facet of ES values. Land price values can vary based on times of economic growth or decline. For example, Wentland et al. (2020) [65] reported a 28% decline in land value during a financial crisis in the last decade without ES valuation. This is a clear evidence that land value and ES value are not connected, which can be an essential consideration for future research. There may be limited instances where the land value is tied to agricultural productivity (provisioning ES). Soil ecosystem goods and services are no longer used locally but are subject to a vast global distribution network, contributing to biogeochemical cycles' destabilization.

3.3.2. Climate Change as a Threat to Pedodiversity

Climate change poses a range of unique threats (e.g., changes in temperature, precipitation, and extreme conditions) to pedodiversity and its ES, which will be discussed following the concept of pedodiversity and its measures outlined in this study. Since pedodiversity (biotic + abiotic) forms from the interaction of various spheres (biosphere, lithosphere, hydrosphere, atmosphere, ecosphere, and anthroposphere), climate change threats will be multifaceted and complex. Both biotic and abiotic aspects of pedodiversity are sensitive to climate change and include the following examples relevant to ED:

- **Biotic** (e.g., increase in soil organic matter decomposition rates due to increase in temperature and precipitation [66] leading to increase in soil CO_2 emissions and associated social costs);
- **Abiotic** (e.g., increase in soil erosion due to an increase in precipitation and extreme rainfall events [67]).

Pedodiversity is influenced by intrinsic (within the soil) and extrinsic (outside soil) factors, where climate change is an extrinsic factor (e.g., changes in temperature, precipitation) with subsequent effect on alterations in intrinsic soil characteristics and properties (e.g., soil temperature and moisture regimes, and moisture content). In terms of taxonomic pedodiversity (diversity of soil classes), climate change poses an existential threat to the soil order of Gelisols. Climate change can lead to changes in soil classification, especially with regards to the use of soil temperature (e.g., pergelic, subgelic, cryic, and frigid) and moisture regimes (e.g., udic and ustic). An example of climate-induced changes in genetic diversity (diversity of soil horizons) includes the potential disappearance of permafrost, which is indicated by the lowercase letter "f" (frozen) in the soil profile. Climate change will impact parametric pedodiversity (diversity of soil properties) in various ways; for example, it can reduce soil organic matter content because of increased decomposition due to temperature. Soil pH can become more acidic because of increased precipitation and leaching, and in the case of agricultural soil, more liming material will need to be applied to compensate for the reduction in provisioning service provided by soil. Functional pedodiversity (soil behavior under different uses) will be affected in many parts of the world because of climate change. For example, global sea rise will influence soils under rice production, resulting in annual crop losses of up to $10.59 billion USD [68].

Projections of future U.S. climate change predict that the entire U.S. is likely to warm over the next 40 years, with an increase of 1–2 °C over much of the country and a 2–3 °C increase in the interior of the country [69]. Reilly et al. (2003) [70] examined the effects of climate change on provisioning ES from U.S. agriculture and reported a potential shift of crop production northwards and a positive overall increase in agricultural production with

regional differences (e.g., possible declines in production in the Southern U.S.). These ES changes are likely to be accompanied by ED in the form of increased social costs associated with carbon dioxide emissions, soil erosion, depletion of soil nutrients, and others, which contribute to the issues of soil and human security worldwide [71]. Climate change in combination with population growth may increase demand for soil nutrients, which replacement from soil weathering is relatively slow in comparison with "anthropogenic use rate" [72]. Since pedodiversity is not evenly distributed within most geographic areas, soil nutrient depletion can be more acute in some places leading to prohibitively high replacement costs associated with fertilizer and liming applications. If the nutrients (e.g., base cations) are not replaced through liming and fertilization, it will alter the soil chemical composition, which can change its pedodiversity classification. Climate change will have a direct impact on the classification of soils, with some soil types disappearing and others changing in both extent and properties. Soil carbon changes associated with climate change and increased organic matter decomposition will also change how soils are classified as they are "decarbonized."

4. Discussion

Pedodiversity is a source of various ecosystem goods, services, and disservices, and its value is as complex as its concept. The total economic value (TEV) of pedodiversity is only a portion of the total system value (TSV) of pedodiversity because pedodiversity and ES form a multilayered relationship with the general trend of decreasing the tangibility of the value of soil to users (Table 3) from the monetary value (e.g., actual use values: consumptive food production) to pedodiversity value (e.g., intrinsic value) (Figure 10) [72,73].

Currently, there are four main approaches to analyze pedodiversity: taxonomic (diversity of soil classes), genetic (diversity of genetic horizons), parametric (diversity of soil properties), and functional (soil behavior under different use). The concept of pedodiversity and its classification varies by country; therefore, its applications to ES are country-specific [74]. According to Gerasimova (2010) [74], "the American Soil Taxonomy is the main and single classification in 45 countries, whereas, in 80 countries, it is used along with the national classifications". Despite differences in country-specific classifications, these soil classifications provide science-based soil information that can be integrated with administrative accounts (Table 2). Taxonomic, genetic, parametric, and functional pedodiversity provide an essential context for analyzing, interpreting, and reporting ES/ED within the ES framework for business applications. Although each approach can be used separately, three of these approaches (genetic, parametric, and functional) fall within the "umbrella" of taxonomic pedodiversity, which separates soils based on properties important to potential use.

Taxonomic pedodiversity provides a general description of the stock, its type, and spatial (both horizontal and vertical) distribution, which are particularly useful in agricultural business applications (e.g., soil productivity ratings in soil survey). For example, an area abundance of soil orders describes the spatial distribution within defined administrative boundaries (e.g., LRRs defined by the USDA based on MLRAs and agricultural markets) (Table 9). The phrases "portfolio effect" and "evenness effect" [75] are often applied to describe the theoretical links between biodiversity and ecosystem function. The "portfolio effect" is the analogy between the stock market and species diversity, where having more species allows a system to better respond to external stimuli. At the same time, the "evenness effect" finds that having similar numbers of species can help buffer against disturbances [76]. The concepts of "portfolio effect,", "evenness effect," and the newly proposed "distribution effect" can also be applied to pedodiversity with various degrees of interpretation (Figures 11 and 12).

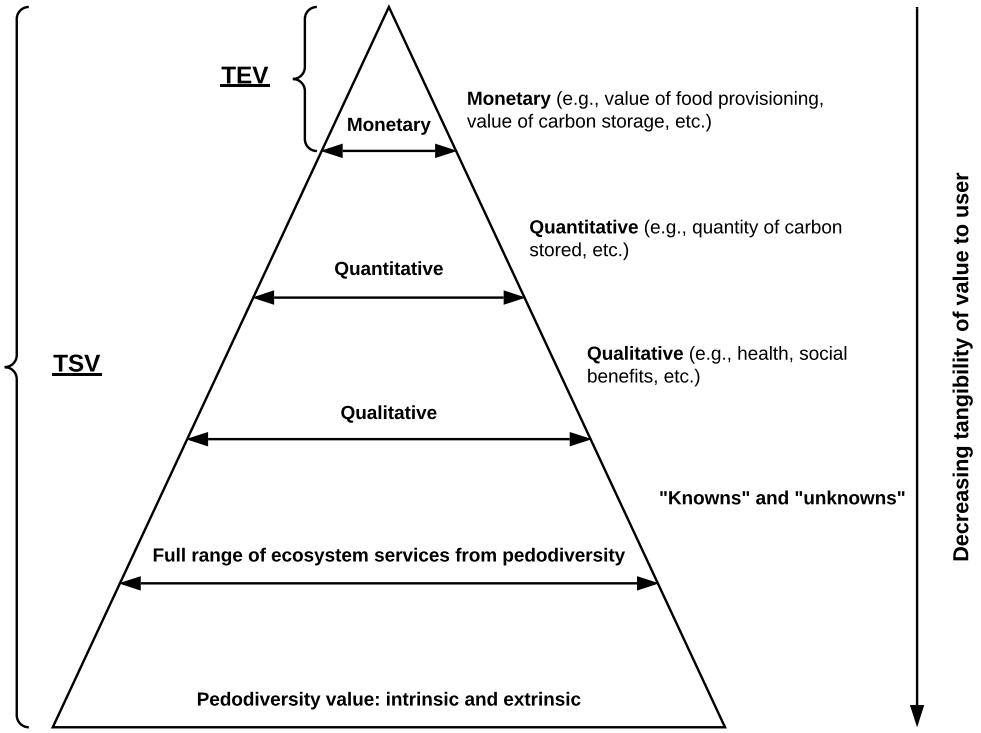

Figure 10. The newly expanded scope of pedodiversity valuation pyramid with a comparison of total economic value (TEV) and total system value (TSV) of ecosystem services (ES) and disservices (ED) (adapted from Gantioler et al., 2000 [76]).

Figure 11 illustrates these concepts using the contiguous United States as an example. In this context, the "portfolio effect" is defined as the number of different stocks (soil orders) within the country (Figure 11). The "distribution effect" shows the distribution of stocks (soil orders), its variation (e.g., slightly-weathered, intermediately-weathered, and strongly-weathered soils), and associated avoided or realized social costs of SOC, SIC, and TSC within the country.

Figure 12 illustrates these concepts using three states (Iowa, Rhode Island, and Georgia). In this context, the "portfolio effect" is defined as the number of different stocks (soil orders) within each state: Iowa (5), Rhode Island (3), and Georgia (7) (Figure 12). The "distribution effect" shows the distribution of stocks (soil orders) and its variation (e.g., slightly-weathered, intermediately-weathered, and strongly-weathered soils) within the state: Iowa (skewed towards intermediately-weathered soils), Rhode Island (skewed towards slightly-weathered soils), and Georgia (skewed towards strongly-weathered soils).

The "evenness effect" describes instances when similar soil types are evenly represented (an example is not shown) (e.g., Mollisols and Alfisols are both fertile soils). For each state, a paired graph shows the proportion of total area occupied by soil order and value of soil organic carbon (SOC) based on avoided social cost of CO_2, with Iowa having largest values, mainly from Alfisols and Mollisols, low total value in Rhode Island, and intermediate value in Georgia based on Ultisols and Histolsols.

Another pedodiversity measure, series density, provides important information about soil diversity, but its interpretation can differ from biological species density. While higher levels of species density are often seen as an advantage when describing biological systems [77], areas with higher soil series density (e.g., typical for soils derived from glacial parent material) may have less agricultural productivity compared with more homogenous and productive soils (e.g., typical for soils derived from loess parent material).

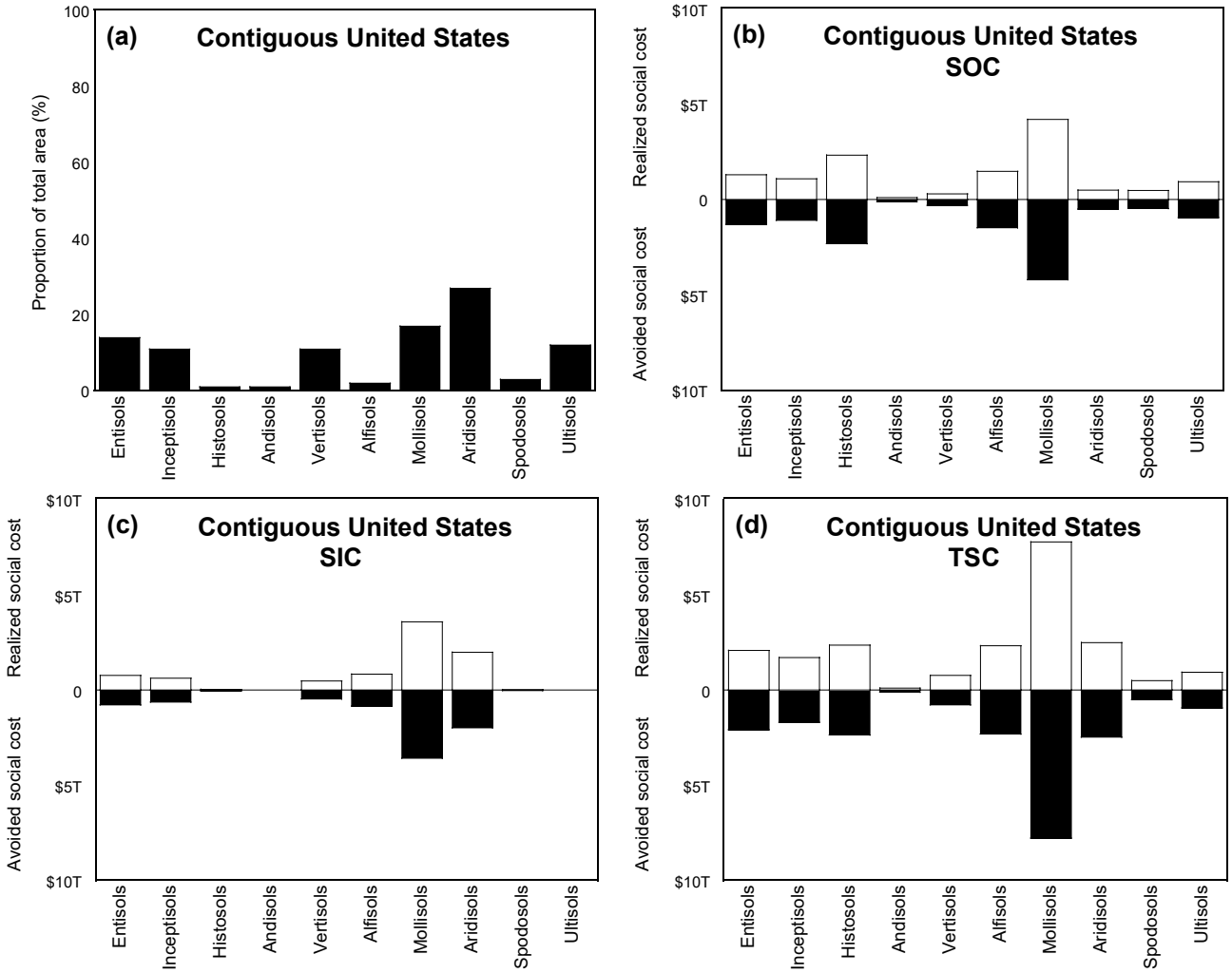

Figure 11. Diagram showing how "portfolio effect" and "distribution effect" of pedodiversity can vary within the country: (**a**) pedodiversity by soil order area; (**b**) value of soil organic carbon (SOC) storage, (**c**) value of soil inorganic carbon (SIC) storage, (**d**) value of total soil carbon (TSC) storage in the upper 2 m depth based on avoided or realized social cost of CO_2 (SC-CO_2) of $42 (USD) per metric ton of CO_2 [30,35,36,51] by soil order. Note: T = trillion = 10^{12}.

Some regions with homogenous soils are characterized by low ES and productivity (e.g., Aridisols). In terms of pedodiversity and ES, it is not just the density or numbers of different soils, but their properties (e.g., chemical and physical) as they relate to the effectiveness (level of performance) and reliability (consistency and predictability) to drive production including agriculture [78]. The soil-to-agricultural market value chain is heavily dependent on large homogeneous areas of soils with high agricultural productivity associated with "soil carbon hotspots" (e.g., Midwest, Northern Plains in the U.S.) [37]. These areas have the most significant pedodiversity loss (and even extinction) and some of the lowest proportion of the U.S. population (Table 12, Figure 5). There is a potential to manage these "hotspots" with precision agriculture technology. It should be noted that not all homogeneous soil areas necessarily have a high ES value.

Loss of pedodiversity may continue, considering projected world population growth [79,80], given that the Midwest and Northern Plains regions export large quantities of agricultural products to the world. Economic estimates focus on the profit from provisioning ES through the sales of agricultural products without considering regulating (e.g., the social cost of pollution including greenhouse emissions) and replacement cost associated with loss of soil nutrients (Figure 6) [80,81].

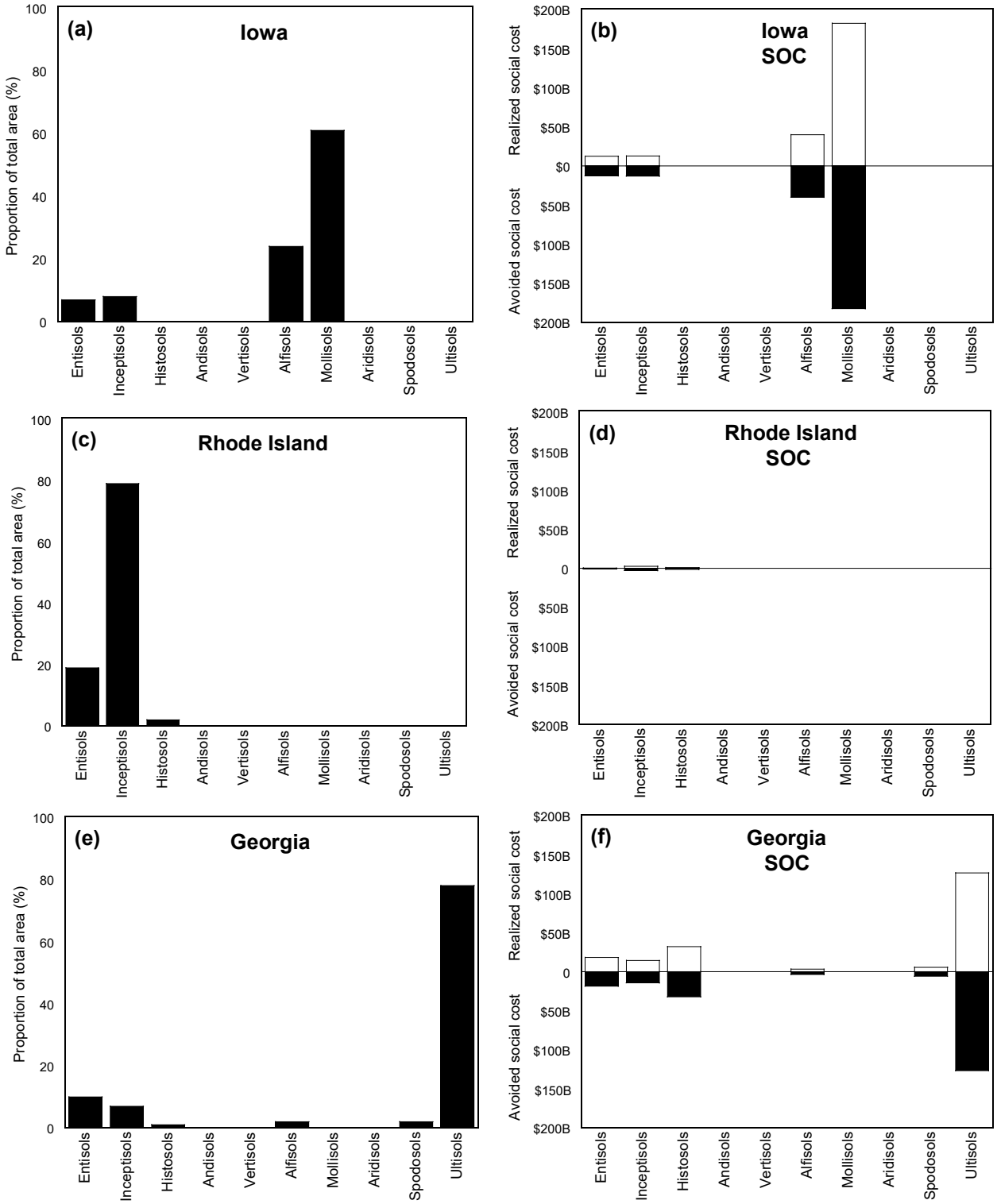

Figure 12. Diagram showing how the "portfolio effect" and the "distribution effect" of pedodiversity can vary by state: (**a**,**c**,**e**) pedodiversity by soil order area; (**b**,**d**,**f**) value of soil organic carbon (SOC) storage in the upper 2 m depth based on avoided or realized social cost of CO_2 (SC-CO_2) of $42 (USD) per metric ton of CO_2 [35,51] by soil order. Note: B = billion = 10^9.

This focus on the direct use value, with little or no regard to the passive and intrinsic use-values, may lead to unsustainable use of pedodiversity (Table 3 and Figure 10). The amount available to replace the lost value of pedodiversity, through insurance value (Table 3) may

not be possible. For example, replacement of some soil nutrients (e.g., phosphorus and potassium) may not be economically feasible since their mineral supply is very limited in the world [81,82]). Estimates of social costs can be performed based on taxonomic pedodiversity (biophysical accounts) (Table 14) and using administrative (boundary-based) accounts (Table 15).

Table 14. Degree of soil development and area-normalized midpoint values of soil organic carbon (SOC) storage in the upper 2 m depth within the contiguous United States (U.S.), based on midpoint SOC numbers from Guo et al., 2006 [39] and a social cost of carbon (SC-CO_2) of $42 (USD) per metric ton of CO_2 [51].

Slight <——— Degree of Weathering and Soil Development ———> Strong					
Slight Weathering		**Intermediate Weathering**		**Strong Weathering**	
Soil Order	**Midpoint SOC Value per Area ($ m^{-2})**	**Soil Order**	**Midpoint SOC Value per Area ($ m^{-2})**	**Soil Order**	**Midpoint SOC Value per Area ($ m^{-2})**
Entisols	1.23	Aridisols	0.62	Spodosols	1.89
Inceptisols	1.37	Vertisols	2.26	Ultisols	1.09
Histosols	21.58	Alfisols	1.16	Oxisols	-
Gelisols	-	Mollisols	2.08		

Biocapacity and ecological footprint are commonly used in environmental carrying capacity (ECC) assessments (e.g., urban areas) [83], and clearly, pedocapacity, or the capacity of the soil to provide various ES, should be a part of these calculations as well. The value of pedocapacity should include both intrinsic (e.g., avoided social costs) and extrinsic (e.g., realized social costs) estimates. Extrinsic realized social costs may be impossible to estimate because their impacts extend beyond the pedosphere boundary, such as in the case of realized social costs of carbon (SC-CO_2) (Figure 13). Limited biocapacity (including pedocapacity) in urban areas often results in urban areas exceeding their ECC, sometimes crossing into other countries [83].

Table 15. Integration of biophysical accounts (science-based) and administrative accounts (boundary-based). Degree of soil development and area-normalized midpoint values of soil organic carbon (SOC) storage in the upper 2 m depth within the contiguous United States (U.S.), based on midpoint SOC numbers from Guo et al., 2006 [39] and a social cost of carbon (SC-CO_2) of $42 (USD) per metric ton of CO_2 [51].

Slight ←——— Degree of Weathering and Soil Development ———→ Strong					
Slight Weathering		**Intermediate Weathering**		**Strong Weathering**	
State (Region)	**Midpoint SOC Value per Area ($ m^{-2})**	**State (Region)**	**Midpoint SOC Value per Area ($ m^{-2})**	**State (Region)**	**Midpoint SOC Value per Area ($ m^{-2})**
Connecticut	2.42	Iowa	3.16	Alabama	1.42
Delaware	4.10	Illinois	1.96	Florida	5.44
Maryland	2.06	Indiana	2.16	Georgia	2.08
Maine	2.54	Michigan	3.71	Kentucky	1.12
New Hampshire	2.40	Minnesota	3.99	Mississippi	1.60
New Jersey	2.56	Missouri	1.36	North Carolina	3.42
New York	2.08	Ohio	1.57	South Carolina	2.77
Pennsylvania	0.91	Wisconsin	3.17	Tennessee	1.09
Rhode Island	2.70	**(Midwest)**	**2.73**	Virginia	1.23
Vermont	2.23			**(Southeast)**	**2.31**
West Virginia	0.74				
(East)	**1.82**				

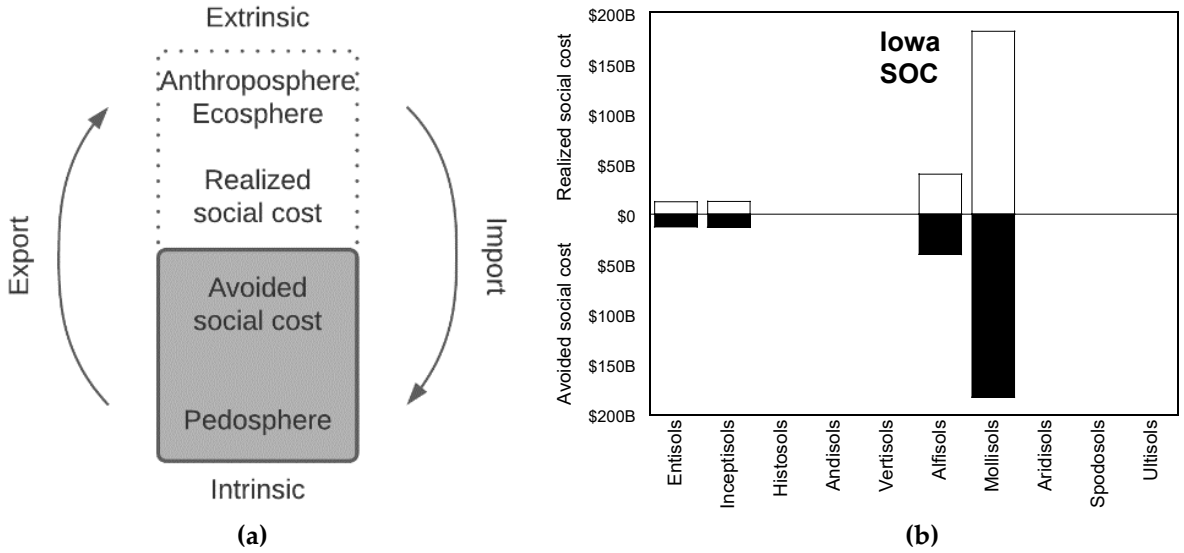

Figure 13. Relationship between intrinsic (e.g., avoided social costs) and extrinsic (e.g., realized social costs) estimates of social costs associated with pedosphere in general (**a**), and using the state of Iowa and soil organic carbon (SOC) as an example (**b**) based on midpoint SOC numbers from Guo et al., 2006 [41] and a social cost of carbon (SC-CO_2) of $42 (USD) per metric ton of CO_2 [51].

Most research efforts are focused on documenting biodiversity loss, but pedodiversity loss can be of catastrophic consequence to humanity; therefore, it is important to understand the extinction patterns and their underlying processes [84]. Global warming has various impacts on the soil, especially on soil organic matter (SOM) decomposition, which is an oxidation process accompanied by oxygen consumption and CO_2 release [85]:

$$\text{R-(C, 4H)} + 2O_2 \rightarrow CO_2\uparrow + 2H_2O + \text{energy (478 kJ mol}^{-1}\text{ C)} \quad (1)$$

The decomposition of SOM, which is accompanied by the release of CO_2 and other gases, accelerates in the presence of increased heat (e.g., global warming) and can be compared to a "fire triangle." Analogous to the "fire triangle," the "SOM decomposition triangle" represents the three items (soil organic matter, oxygen, and heat) that feed SOM decomposition emissions of CO_2 and other invisible gases that fuel global warming (Figure 14). Unlike a regular fire, which is visible, the invisible greenhouse gases are like an invisible "fire" that can only be prevented and minimized by identifying the location of "fuel loading" (soil organic matter) throughout the landscape.

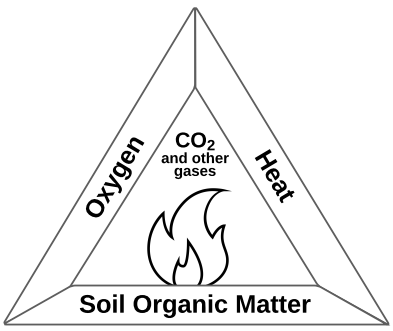

Figure 14. The "SOM decomposition triangle" represents the three items (soil organic matter, oxygen, and heat) that feed soil decomposition emissions of CO_2 and other gases that fuel global warming.

The Earth's regions and soils with high SOM levels (e.g., Histosols, Gelisols, Alfisols, Mollisols, and Vertisols) tend to be more susceptible to greenhouse gas emissions with increasing global temperatures. Histosols and Gelisols are of particular concern because they are threatened by draining (Histosols) and thawing (Gelisols), which can cause soil degradation with global consequences [86,87]. For example, Pastick et al. (2015) [86] reported that 16 to 24% (out of 38%) of near-surface permafrost will disappear by the end of the 21st century. States and regions with a higher proportion of their area occupied by high-risk soils ("hotspots") [37] are experiencing the highest losses in ES (especially in provisioning), which is often caused by the demand for ES (e.g., provisioning) outside their boundaries. According to Hansjurgens et al. (2018) [88], pedodiversity distribution around the world poses an important question about "fairness" not only in the provisioning of ES but also in the associated and past ED costs. Administrative accounts (e.g., states and regions) in combination with pedodiversity concepts can provide information to develop cost-effective policy options to manage benefits (ES) and risks (ED) from pedodiversity. These benefits and risks often extend beyond the boundaries of individual states and regions (e.g., greenhouse emissions), therefore creating a need for a long-term coordinated vision, collaboration, and monitoring. It should be noted that both the ES framework and its valuation measures are human-centric, bias, and focused on short-term human scale interests instead of treating and valuing pedodiversity at a long-term geologic time scale [12,20]. According to Table 3 and Figure 10, pedodiversity tangibility values tend to decrease from "actual use" values to "intrinsic" values (benefits to nature). Soil series are often associated with these monetary "actual use" values (e.g., provisioning: food, etc.) because they represent soil properties within property boundaries in contrast to soil orders, which are often associated with large spatial extents which cross multiple property boundaries representing "intrinsic" values and social costs (Figure 15). According to Guerry et al. (2015) [89], "perhaps the most difficult challenge in the path of success is removing the fundamental asymmetry at the heart of economic systems, which rewards the production of marketed commodities but not the provision of nonmarketed ecosystem services or the sustainable use of natural capital that supports these services."

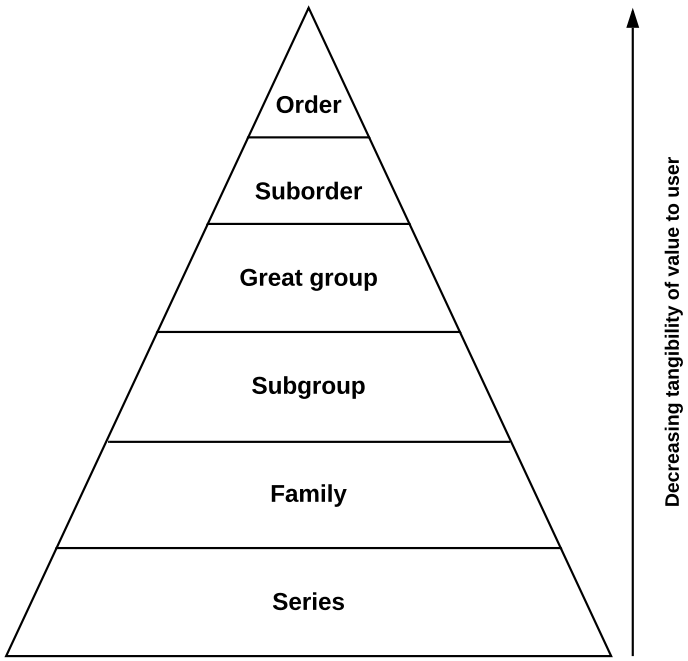

Figure 15. Taxonomic pedodiversity and tangibility of value to the user (adapted from Soil Survey Staff, 1999 [15]).

Market transformations of pedodiversity can result not only in welfare but damages as well [90], which can pose a threat to soil security, national security, food security, infrastructure, and human life [91–93]. Pedodiversity can be both valuable and problematic to human well-being, depending on the point of view. The value of pedodiversity is that it is a human construct, which is used to "categorize" the soil continuum in a discrete way [93] and can be applied to ES/ED within administrative boundaries for socio-economic analysis. The problem with the discretization of both soils and related ES/ED is that it can oversimplify the complex nature of pedodiversity, which is a product of the interaction between the Earth's various spheres and their diversities (Figure 1). For example, Bach et al. (2020) [94] discusses the contribution of soil biodiversity to ES, which varies by soil type (taxonomic pedodiversity) and would require integration of pedodiversity with soil biodiversity for sustainable soil management. Human activity (e.g., agriculture and urbanization) can erode soil pedodiversity by converting soils to more uniform human-altered soils (Anthrosols) with a reduction in soil ES [95]. The perception of pedodiversity [96] and its contribution to ES/ED depends on the human "behavioral dimensions" ("human nature"), which are less understood in both perceived ES benefits and ED, especially with regards to regulating ES/ED (e.g., greenhouse gas emission) which tend to be of global significance [97].

5. Conclusions

This study examined the application of soil diversity (pedodiversity) concepts (taxonomic, genetic, parametric, and functional) and its measures to value ES/ED with examples based on the contiguous United States (U.S.), its administrative units, and the systems of soil classification (e.g., U.S. Department of Agriculture (USDA) Soil Taxonomy, Soil Survey Geographic (SSURGO) Database). Pedodiversity provides an important context (e.g., "portfolio effect", "distribution effect", and "evenness effect") for analyzing, interpreting, and reporting ES/ED within the ES framework for business applications. Taxonomic pedodiversity in the contiguous U.S. exhibits high soil diversity, which is not evenly distributed within administrative units. Pedodiversity distribution around the country poses an important question about "fairness" not only in the provisioning of ES but also in the associated and past ED costs. Pedodiversity in the U.S. is under various threats, including land cover change (urbanization, agriculture, deforestation) and climate change (existential threat to the soil order of Gelisols). Pedodiversity losses are especially high in agriculturally productive and important soils (e.g., Alfisols, Mollisols) and regions (e.g., Midwest, Northern Plains, South Central) with some of the lowest proportions of U.S. total population. There is a mismatch between "potential" and "realized" supply/demand of flow-dependent ES/ED. With over 80% of the U.S. population living in urban environments, there is an increase in demand for ES, which is not always supplied by local soil resources and requires soil ecosystem goods and services to be "imported" from other geographic areas. The flow of ecosystem goods and services is often accompanied by the expansion of agricultural areas based on available soil resources. Low-fertility soils and other extrinsic factors (e.g., low precipitation) may limit the flow of ecosystem goods and services. Climate change will have a direct impact on pedodiversity and the classification of soils, with some soil types disappearing and others changing in both extent, and properties. Administrative accounts (e.g., states and regions) in combination with pedodiversity concepts can provide information to develop cost-effective policy options to manage benefits (ES) and risks (ED) from pedodiversity. These benefits and risks often extend beyond the boundaries of individual states and regions (e.g., greenhouse emissions), creating a need for a long-term coordinated vision, collaboration, and monitoring.

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Abbreviations

ED	Ecosystem disservices
ES	Ecosystem services
EPA	Environmental Protection Agency
SC-CO_2	Social cost of carbon emissions
SDGs	Sustainable Development Goals
SOC	Soil organic carbon
SIC	Soil inorganic carbon
SOM	Soil organic matter
SSURGO	Soil Survey Geographic Database
TEV	Total economic value
TSV	Total system value
USDA	United States Department of Agriculture
US	United States

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