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Spatiotemporal Analysis of Soil Quality Degradation and Emissions in the State of Iowa (USA)

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Abstract: The concept of soil quality (SQ) is defined as the soil's capacity to function, which is commonly assessed at the field scale. Soil quality is composed of inherent (soil suitability) and dynamic (soil health, SH) SQ, which can also be analyzed using geospatial tools as a SQ continuum (SQC). This study proposes an innovative spatiotemporal analysis of SQ degradation and emissions from land developments using the state of Iowa (IA) in the United States of America (USA) as a case study. The SQ degradation was linked to anthropogenic soil (SD) and land degradation (LD) in the state. More than 88% of land in IA experienced anthropogenic LD primarily due to agriculture (93%). All six soil orders were subject to various degrees of anthropogenic LD: Entisols (75%), Inceptisols (94%), Histosols (59%), Alfisols (79%), Mollisols (93%), and Vertisols (98%). Soil and LD have primarily increased between 2001 and 2016. In addition to agricultural LD, there was also SD/LD caused by an increase in developments often through urbanization. All land developments in IA can be linked to damages to SQ, with 8385.9 km^2 of developed area, causing midpoint total soil carbon (TSC) losses of 1.7 × 10^{11} kg of C and an associated midpoint of social cost of carbon dioxide emissions (SC-CO_2) of $28.8B (where B = billion = 10^9, USD). More recently developed land area (398.5 km^2) between 2001 and 2016 likely caused the midpoint loss of 8.0 × 10^9 kg of C and a corresponding midpoint of $1.3B in SC-$CO_2$. New developments are often located near urban areas, for example, near the capital city of Des Moines, and other cities (Sioux City, Dubuque). Results of this study reveal several different kinds of SQ damage from developments: loss of potential for future C sequestration in soils, soil C loss, and "realized" soil C social costs (SC-CO_2). The state of IA has very limited potential land (2.0% of the total state area) for nature-based solutions (NBS) to compensate for SD and LD. The results of this study can be used to support pending soil health-related legislation in IA and monitoring towards achieving the Sustainable Development Goals (SDGs) developed by the United Nations (UN) by providing a landscape-level perspective on LD to focus field-level initiatives to reduce soil loss and improve SQ. Future technological innovations will provide higher spatial and temporal remote sensing data that can be fused with field-level direct sensing to track SH and SQ changes.

Keywords: carbon; climate; greenhouse gas; Sustainable Development Goals; United Nations; UN

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1. Introduction

Soil quality (SQ) is one of the three components (soil, water, and air quality) of environmental quality, which are commonly characterized by their pollution status concerning human, animal, and ecosystem health [1,2]. The concept of SQ has a broader interpretation as "*the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health*", where human health is part of animal health [3,4]. Soil quality (SQ) is also defined as the soil's capacity to function, which is commonly assessed at the field scale [5]. Soil quality is composed of inherent (soil suitability) and dynamic (soil health) SQ (Figure 1) [5]. Inherent SQ is determined by its natural ability to function, which relates to soil's natural physical, chemical, and biological properties used to classify soil types (e.g., United States Soil Taxonomy [6]). Dynamic soil quality (soil health) is defined as "*the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans*" [7]. It describes the soil changes because of land management (e.g., cultivation) [5], which are assessed by SQ indicators used to compute the overall SQ index [8]:

- **Physical:** bulk density; soil texture and structure; aggregate stability; porosity; plant available water; hydraulic conductivity and infiltration;
- **Chemical:** organic and total carbon (C); organic and total nitrogen (N); available nutrients (phosphorous, P; potassium, K); soil reaction (pH); electrical conductivity; cation exchange capacity (CEC); carbonates;
- **Biological:** microbial biomass; microbial respiration; microbial community composition; enzymatic activity; earthworms; nematodes.

The original concept of SQ further evolved into emphasizing the soil health (SH) side of SQ, and there are ongoing discussions about whether SQ and SH are the same or different concepts [8]. The focus of this study is on SQ based on its definition in Figure 1 and its chemical indicators: organic and total C. The inherent SQ in Iowa (IA) is represented by the soil diversity (pedodiversity) of the state, which is composed of six soil orders: slightly weathered soils (Histosols, Inceptisols, and Entisols), and moderately weathered soils (Mollisols, Alfisols, and Vertisols), with various inherent soil qualities (Table S1; Figure 2). Iowa has selected Tama as the State Soil (soil order: Mollisols) because it is the most productive soil for agriculture in the state [9]. The inherent SQ of IA is dominated by soil orders of Mollisols (60.9%) and Alfisols (23.9%), which are often inherently high-fertility soils important in agriculture.

Agriculture in IA is the leading cause of dynamic SQ (soil health) degradation. Numerous field studies were conducted to examine dynamic SQ in IA at various scales (e.g., watershed, field, etc.). For example, Karlen et al. (2008) used watershed SQ assessment in North Central IA to minimize soil and water pollution from manure application and soil C loss from tillage [10]. Cambardella et al. (2004) [11] conducted a watershed-scale analysis of SQ in the loess hills of southwest IA and concluded that SQ degradation was impacted by landscape position and distribution of soil properties. Stott et al. (2011) [12] utilized SQ assessment, which included soil C and landscape position within the IA River South Fork watershed to distinguish SQ between corn fields with well-developed and poorly developed corn canopy. Another watershed-scale study in Clear Creek (IA) examined soil organic matter (SOM) loss and SQ [13].

Figure 1. Soil quality is composed of inherent and dynamic soil quality (adapted from De la Rosa and Sobral, 2008 [5]).

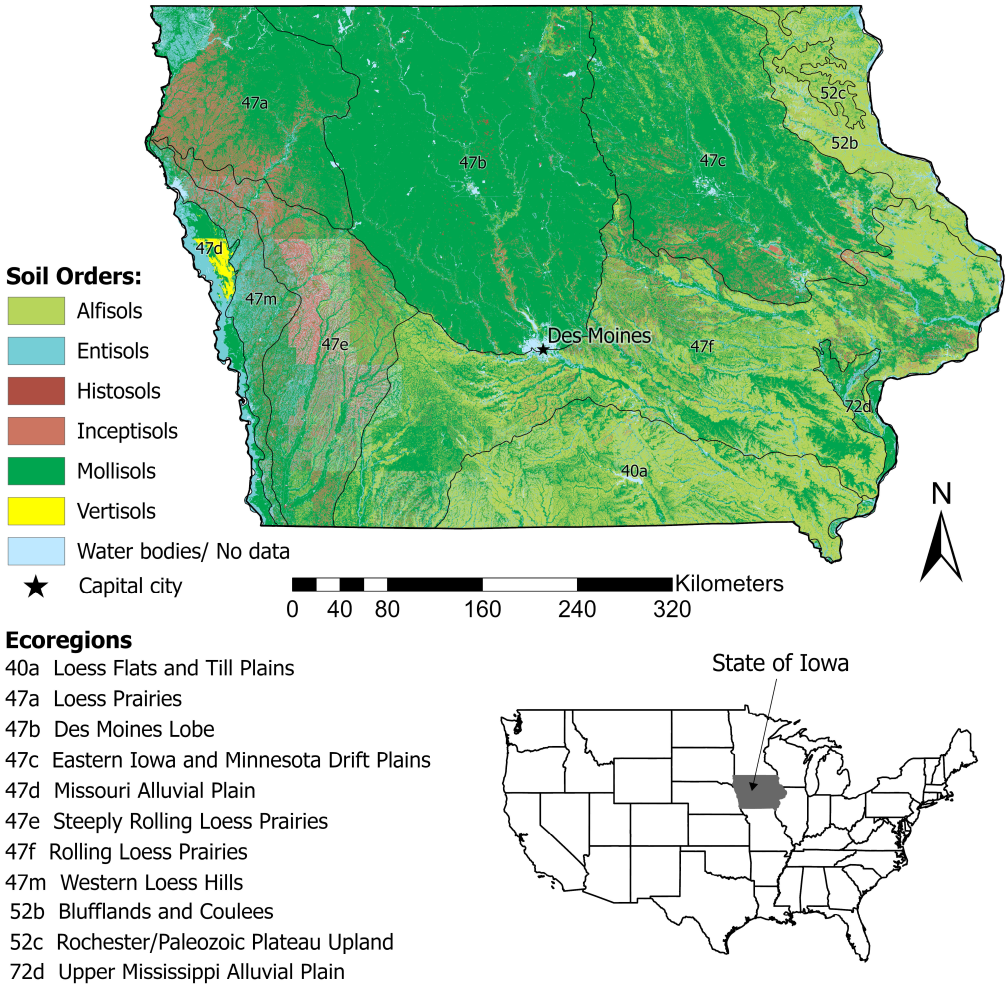


Figure 2. Soil map for the state of Iowa (IA), USA, (40° 36′ N to 43° 30′ N and 89° 5′ W to 96° 31′ W) developed using the SSURGO spatial soils database [14] and ecoregions [15]. It shows the spatial distribution of soil orders with different inherent soil qualities (soil suitability). The inherent soil quality of IA is dominated by soil orders of Mollisols (60.9%) and Alfisols (23.9%), which are often inherently high-fertility soils important for agriculture.

Most field-scale SQ studies in IA focused on the effects of tillage and cropping on various SQ indicators [16–18] and SOM in particular [19,20]. The SQ degradation in IA is closely linked with the state's history of soil utilization by various users, from Native Americans [21] to European settlers [22]. Gallant et al. (2011) [22] documented changes in land cover from the mid-1800s to ~2001 and found that grasslands originally covered 80% of IA, while woodlands covered 18% of the state. By 2001, 85% of the grasslands were converted to agricultural uses (75% cropland and 10% hay/pasture), while only 7% of the state had woodlands [22]. These land cover changes caused massive SQ degradation through the conversion of grasslands and forests to agricultural land uses (Table 1). In the 1800s less than 1% of IA was considered urbanized, compared to 7% urbanization by 2001 [22]. Currently, Streeter et al. (2019) [23] advocate examining dynamic SQ (soil health) across the agricultural/urban gradient to help distinguish the specific impacts of urbanization and agriculture on SQ. A comparison of soils in the Charles City urban cluster and soils in the agricultural area in IA revealed detectable differences in SQ of urban and agricultural soils [23].

Much of the past SQ research has focused on field-scale agronomic measurements and analysis [16,19]; however, SQ research can be extended to landscape scale evaluation to help understand overall SQ and its change over time, which represents impacts from land management.

Table 1. Ecoregions of Iowa (IA) and changes in land use/land cover of potential natural vegetation (adapted from Griffith et al., 1994 [24]).

Ecoregion	Soil Order	Potential Natural Vegetation	Land Use/Land Cover
Loess Flats and Till Plains (40a)	Mollisols	Oak-hickory forest, mosaic of bluestem prairie	Cropland, pasture, deciduous forest
Loess Prairies (47a)	Mollisols	Bluestem prairie	Cropland
Des Moines Lobe (47b)	Mollisols	Bluestem prairie	Cropland
Eastern Iowa and Minnesota Drift Plains (47c)	Mollisols	Bluestem prairie, oak-hickory forest	Cropland
Missouri Alluvial Plain (47d)	Mollisols	Oak-hickory forest, northern floodplain forest	Cropland
Steeply Rolling Loess Prairies (47e)	Mollisols	Bluestem prairie, oak-hickory forest	Cropland
Rolling Loess Prairies (47f)	Mollisols, Alfisols	Oak-hickory forest, mosaic of bluestem prairie	Cropland, small areas of deciduous forest
Western Loess Hills (47m)	Mollisols	Oak-hickory forest, bluestem prairie	Cropland
Blufflands and Coules (52b)	Alfisols	Maple-basswood forest	Cropland, pasture, deciduous forest
Rochester/Paleozoic Plateau Upland (52c)	Alfisols	Maple-basswood forest	Cropland, pasture, deciduous forest
Upper Mississippi Alluvial Plain (72d)	Alfisols, Mollisols	Oak-hickory forest	Cropland, deciduous forest, forested wetlands

Furthermore, the quantification of SQ at the landscape scale can identify critical areas where dynamic SQ (soil health; Figure 3) has changed, which can be represented by differences in SQ over time and space through conversions between different land covers (e.g., developed, agriculture, barren, etc.). This research aims to extend the understanding of SQ to the landscape scale by using remote sensing analysis combined with geospatial analysis of soils impacted by land use and land change. These changes in land cover can indicate likely changes in overall SQ, where the SQ can be improving (aggrading), maintaining the same level (sustaining), or deteriorating (degrading) (Figure 4). Inherent SQ is largely based on soil type (Figure 3) and including soil type in geospatial analysis can help understand and prioritize remediation associated with SQ degradation.

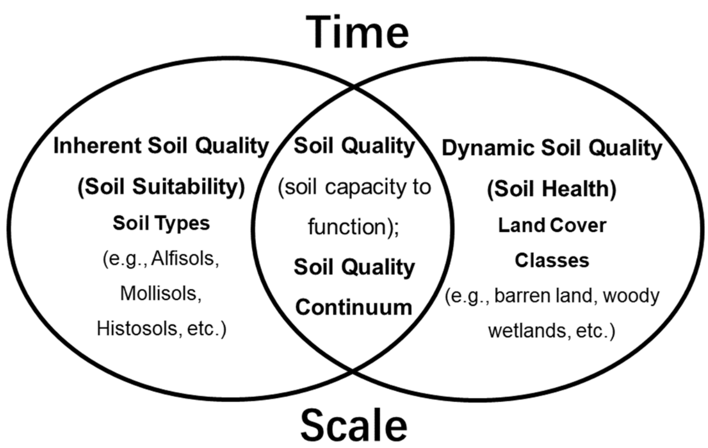


Figure 3. Soil quality is concisely defined as the soil's capacity to function [5], which can be understood as the intersection of land cover and/or land use/land cover (LULC) change and soil type and over scale and time (adapted from Karlen et al., 2019 [25]). The SQ continuum is a series of values that differ with LULC and soil type.

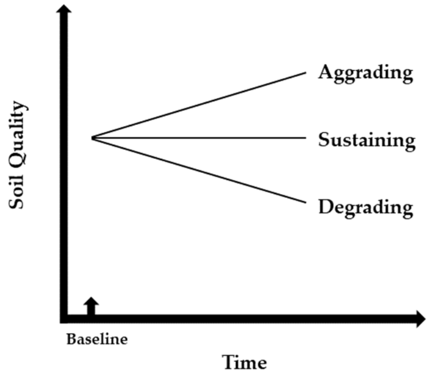


Figure 4. Concept of soil quality trends with time (adapted from Seybold et al., 1998 [26]).

Changes to SQ at the landscape level are driven by disturbances, with human development (urbanization) likely providing the largest, often irreversible, degradation of SQ. One of the main impacts of disturbance to SQ is the loss of soil C and increased soil C emissions, which can be represented as monetary loss through the concept of the social cost of carbon (SC-CO_2) [27,28]. Landscape-scale analysis and tracking of SQ over time (including through past land cover change analysis) have the potential to allow the spatial evaluation of overall SQ to identify soil resources that have likely degraded while also providing overall estimates of soil C losses. The present study hypothesizes that the SQ continuum (inherent SQ based on soil type as well as dynamic soil health status that varies by LULC) can be analyzed using geospatial analysis combining soil type and LULC. The common unit of study for SQ is the agricultural field scale, with the primary focus on the evaluation of soil physical, chemical, and biological indicators. Our study takes a different approach by focusing on mapped soil types (inherent SQ) and geospatial analysis of land cover change (dynamic SQ) at the landscape level to help understand overall SQ. The inherent soil properties available from detailed spatial soil databases are closely linked to soil classification [1], which, in combination with dynamic SQ (soil health) represents the SQ continuum. Soil quality status over time can be understood as either aggrading (improving), sustaining (with no change), or degrading with SQ loss (Figure 4) [26]. Soil quality degradation can be caused by soil disturbance, which releases GHGs and degrades soil function. Soil disturbance levels can be inferred from land cover and land cover changes over time. It is important to note that the pre-agricultural status of many current agricultural areas was prairies with high SQ [22]. This study proposes a method to evaluate landscape-level SQ that could be used to prioritize soil monitoring of areas where soil resources are threatened for intervention and remediation. This study fills a scientific gap in how to conceptualize, understand, and quantify SQ as an overall resource at multiple spatial scales ranging from the field to various administrative levels (e.g., state, county, etc.).

This study aimed to: (1) characterize inherent SQ (soil suitability) in IA, including soil C storage, (2) identify the SQ continuum using soil and land cover analysis; (3) link SQ degradation to different types of land degradation (total, barren, developed, agriculture); (4) quantify changes in SQ over 15 years (2001–2016) using land cover change analysis to identify changes in barren, developed, and agricultural land cover categories; (5) identify a land area for potential nature-based solutions to counteract SQ degradation; (6) quantify the total soil C (TSC) loss from SQ degradation caused by human developments (urbanization) over 15 years considering associated emissions and the social cost of C (SC-CO_2), assumed to be $46 per CO_2 metric tonne emitted (applicable for the year 2025 using 2007 U.S. dollars and an average discount rate of 3% provided by the US Environmental Protection Agency (EPA)) [28]. Monetary value estimates for TSC within the state of IA are provided by this study at various aggregation levels from the State Soil Geographic (STATSGO) [29], Soil Survey Geographic Database (SSURGO) [14], and the data given by Guo et al. (2006) [30].

2. Materials and Methods

The present study used an integrated, geographical plus economic framework to investigate the SQ status and its changes in the state of IA (Table S2 [27]). Land cover spatial datasets, classified from Landsat satellite image mosaics at a 30-m resolution, were acquired from the Multi-Resolution Land Characteristics Consortium (MRLC) [31] and used to track changes in land use/land cover across the state of IA from 2001 to 2016. Land cover changes by soil order, counties, etc., were calculated using ArcGIS Pro 2.6 [32] after converting the raster land cover data to a vector format and then performing a union operation on the resulting dataset with the other corresponding datasets having the same spatial extent. For example, land cover changes by soil type used the Soil Survey Geographic (SSURGO) [14] Database because it provides the most detailed soils data available at the national level at various taxonomic categories [6].

Monetary values of SIC, SOC, and TSC were calculated for these SQ indicators and tracked by soil order, county, etc. (Figure 2 and Table S2). Soil carbon contents (kg m^{-2}) as reported by Guo et al. (2006) [30] were used to calculate area-normalized monetary values (\$ m^{-2}) based on the EPA social cost of carbon (SC-CO_2) value of \$46 per metric ton of CO_2 [28] (Table S3) as shown in Equation (1), where SC represents soil carbon and a metric tonne is equal to 1000 kg or 1 megagram (Mg):

$$\frac{\$\ \text{USD}}{\text{m}^2} = \left(\text{SC Content}, \frac{\text{kg}}{\text{m}^2}\right) \times \frac{1\ \text{Mg}}{10^3\ \text{kg}} \times \frac{44\ \text{Mg CO}_2}{12\ \text{Mg SC}} \times \frac{\$46\ \text{USD}}{\text{Mg CO}_2} \quad (1)$$

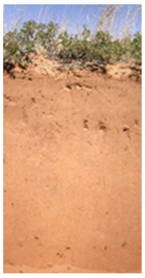
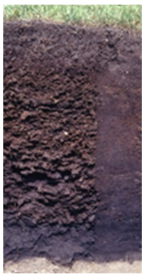
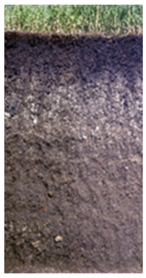
Total monetary estimates then were determined by summing the area-normalized values from Equation (1) over suitable spatial boundaries. For example, Guo et al. (2006) [30] reported a midpoint SOC content estimate of 7.5 kg m^{-2} for the soil order Alfisols (Table S3). Equation (1) therefore shows the area-normalized monetary value associated with SOC in Alfisols to be \$1.27 m^{-2}. Multiplying the SOC content and corresponding area-normalized monetary value by the total area of Alfisols in IA (34,090.3 km^2) results in a calculated SOC stock of 2.6×10^{11} kg C which has a corresponding monetary value of \$43.3B. It is important to note that this calculated monetary value, however, likely underestimates the true costs and damages resulting from CO_2 emissions. Although the EPA developed its SC-CO_2 value to estimate damage due to climate change, it excludes a number of potential climate change impacts that have been identified in the scientific literature [28].

3. Results

3.1. Inherent Soil Quality (Soil Suitability) and Soil Carbon Storage in Iowa

The inherent SQ in Iowa (IA) is represented by the soil diversity (pedodiversity) of the state, which is composed of six soil orders: slightly weathered soils (Histosols, Inceptisols, and Entisols), and moderately weathered soils (Mollisols, Alfisols, and Vertisols), with various inherent soil qualities (Table 2). The inherent SQ of IA is dominated by soil orders of Mollisols (60.9%) and Alfisols (23.9%), which are often inherently high-fertility soils important for agriculture. This study is primarily focused on soil C as one of the most important SQ indicators. Iowa soil is a critical non-renewable resource with varying C levels. Total mid-point storage and SC-CO_2 estimated values for TSC within IA (2016) were 2.1×10^{12} kg C and \$488.0B (i.e., \$488.0B billion U.S. dollars, where B = billion = 10^9), respectively (Table 2). From these estimated totals, SIC represented 22% of the overall content (4.7×10^{11} kg C, \$211.6B) and SOC represented 78% of the overall content (1.6×10^{12} kg C, \$276.4B). We previously reported that IA was ranked 5th for SOC [33], 8th for TSC [34], and 9th for SIC [27], for SC-CO_2 values within the 48 conterminous U.S. states. Reported soil C levels are the remaining contents after historic land conversions. This overall soil C accounting for the state gives an important metric to help evaluate the comprehensive "soil bank" SQ. It is important to note that SQ assessments typically do not incorporate SIC, which is linked to soil pH, a frequent indicator of SQ [8]. Soil C is likely the most important SQ indicator because it directly influences the physical, chemical, and biological SQ indicators. Also, it is a key component of dynamic SQ (soil health) and can be used to monitor SQ dynamics and status over time (aggrading, sustaining, degrading). Importantly, change in soil C is directly linked to GHG emissions and climate change, with soil disturbance resulting in GHG emissions. Considering the high remaining soil C storage in IA, there is a large potential for GHG emissions from IA soils upon their disturbance, which needs to be quantified and monitored regularly.

Table 2. Distribution of inherent soil quality (soil suitability) and carbon (an important soil quality indicator) regulating ecosystem services in the state of Iowa (IA) (USA) organized by soil order (photos from USDA/NRCS [35]) in 2016.

Inherent Soil Quality (Soil Suitability) and Soil Regulating Ecosystem Services in the State of Iowa (USA)					
Lower	←			→	**Higher**
Soil Regulating Ecosystem Services in Iowa					
Degree of Weathering and Soil Development					
Slight (15.0%)			**Moderate (85.0%)**		
Entisols	**Inceptisols**	**Histosols**	**Alfisols**	**Mollisols**	**Vertisols**
6.4%	**8.5%**	**0.1%**	**23.9%**	**60.9%**	**0.2%**
					
Midpoint storage and social cost of soil organic carbon (SOC): 1.6× 10^{12} kg C, $276.4B					
7.4 × 10^{10} kg	1.1 × 10^{11} kg	2.1 × 10^{10} kg	2.6 × 10^{11} kg	1.2 × 10^{12} kg	4.3 × 10^{9} kg
$12.4B	$18.1B	$3.5B	$43.3B	$198.3B	$730.8M
4.5%	6.6%	1.3%	15.7%	71.8%	0.3%
Midpoint storage and social cost of soil inorganic carbon (SIC): 4.7× 10^{11} kg C, $211.6B					
4.4 × 10^{10} kg	4.7 × 10^{10} kg	2.2 × 10^{10} kg	4.0 × 10^{10} kg	1.1 × 10^{11} kg	2.1 × 10^{11} kg
$7.5B	$10.4B	$60.8M	$24.5B	$167.9B	$1.2B
3.6%	4.9%	0.0%	11.6%	79.4%	0.5%
Midpoint storage and social cost of total soil carbon (TSC): 2.1× 10^{12} kg C, $488.0B					
1.2 × 10^{11} kg	1.7 × 10^{11} kg	2.1 × 10^{10} kg	4.0 × 10^{11} kg	2.2 × 10^{12} kg	1.1 × 10^{10} kg
$19.9B	$28.5B	$3.6B	$67.8B	$366.2B	$1.9B
4.1%	5.8%	0.7%	13.9%	75.0%	0.4%
Sensitivity to climate change					
Low	Low	High	High	High	High
SOC and SIC sequestration (recarbonization) potential					
Low	Low	Low	Low	Low	Low

Note: Entisols, Inceptisols, Alfisols, Mollisols, and Vertisols are mineral soils. Histosols are most often considered organic soils. M = million = 10^6; B = billion = 10^9; USD = United States Dollar ($). Supplemental Table S4 lists minimum and maximum values.

3.2. Dynamic Soil Quality (Soil Health) and Soil Quality Continuum in Iowa

The SQ continuum is comprised of the land cover status available from the 2016 NLCD data, combined with information on the inherent soil capabilities that can be derived from the spatial soil databases. Soil order and land cover information can be interlinked and considered together (Table 3), where levels of soil disturbance can be understood based on the land cover. In this way, land covers with minimal regular disturbance (e.g., forest and wetland land cover types) can be compared with areas with cultivated crops (medium disturbance) and human developments (typically high levels of disturbance). Land cover and the SQ continuum for the state of IA are dominated (~70%) by cultivated crops, which are a medium soil disturbance regime. Developments are found in greater than 5.9% of the state, and the remaining 24% are under land cover types that represent lower disturbance. The dominant agricultural land cover is evident when examining the state land cover map (Figure 5). That information can be visually combined with the soil distribution map (Figure 2), highlighting the prevalence of the highly productive soil orders of Alfisols and Mollisols. The agricultural land uses, with their disturbance regime, are located throughout IA because of the soils that have characteristics to support productive agriculture.

It is important to reiterate that the inherent SQ or suitability of soil is based on the soil's chemical and physical properties without considering the human-related disturbance regime associated with a particular area of soil. Determining a disturbance level can be challenging because of the range of types of practices within a land cover category. For example, agricultural practices can include low-disturbance (pasture/no-till) to high disturbance (regular tilling), which impact soils and soil C differently. Current satellite-based land cover data allows the general classification of land cover (associated with a range of land-use practices), which can be evaluated yearly.

Significant research has focused on soil health at the agronomic field scale, where the relationship between practices and soil health is evaluated and tracked over time. Additionally, soil testing, including soil physical and chemical properties, has long been used to evaluate and track the soil's capacity to support specific agronomic crops. Unfortunately, most of these efforts have largely ignored the overall landscape-level soil resources because of their agronomic focus. Land cover change analysis over decades shows that soils can go between various land uses over decades, with both consumptive (e.g., development) and potentially restorative changes (e.g., till agriculture to forestry or pasture).

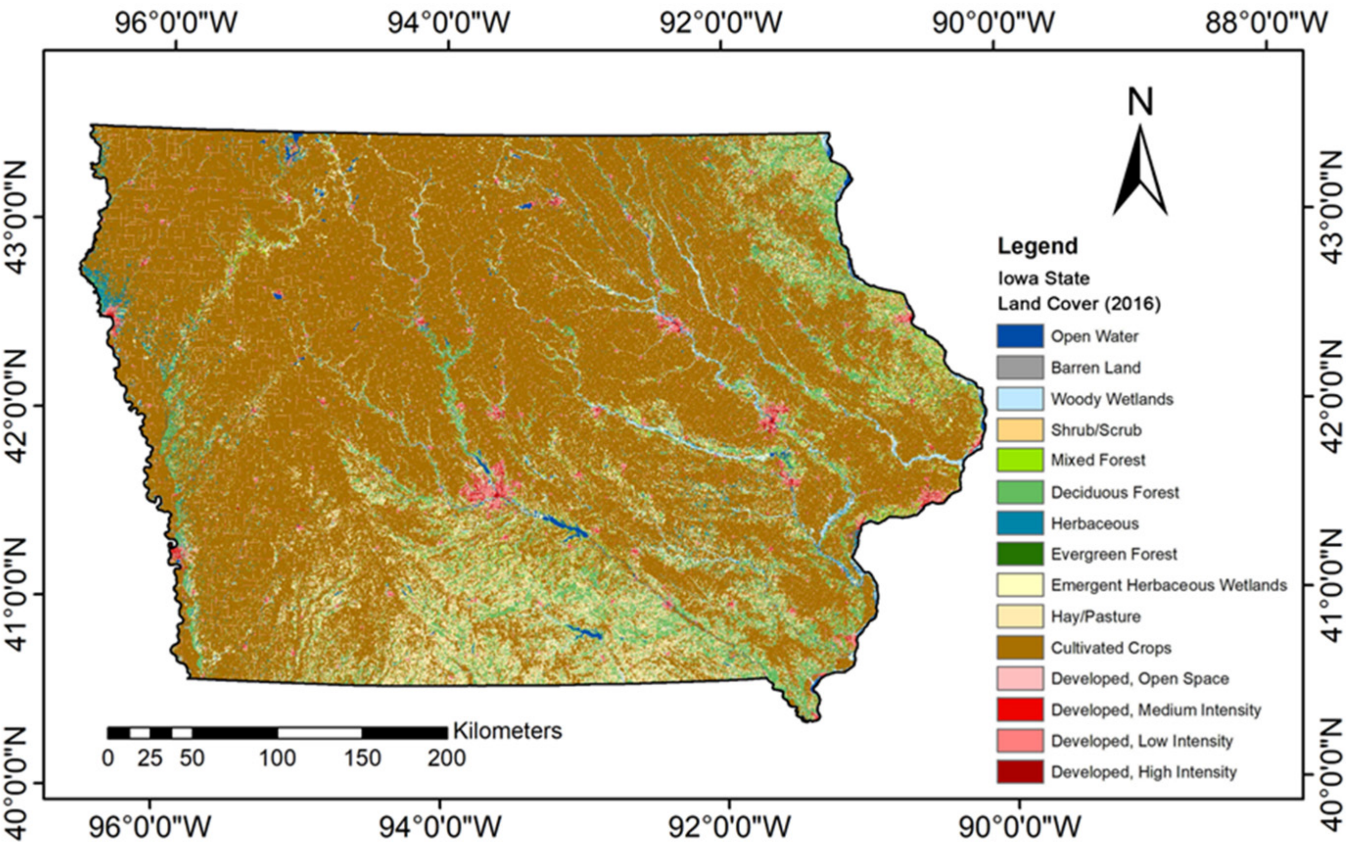


Figure 5. State of Iowa (IA) (USA) 2016 land cover map (40° 36′ N to 43° 30′ N and 89° 5′ W to 96° 31′ W) (using data from MRLC [31]) showing dynamic soil quality (soil health).

Table 3. The soil quality continuum was represented by the state of Iowa (IA) (USA) land use/land covers (LULC) and soil order areas in 2016.

Soil Quality Continuum								
NLCD Land Cover Classes (LULC), Dynamic Soil Quality (Soil Health Continuum)		2016 Total Area by LULC (km^2, %)	Inherent Soil Quality (Soil Suitability): Lower ← → Higher					
			Degree of Weathering and Soil Development					
			Slight			Moderate		
			Entisols	Inceptisols	Histosols	Alfisols	Mollisols	Vertisols
			2016 Area by Soil Order (km^2)					
Woody wetlands	Higher	1737.9 (1.2)	574.1	12.0	4.9	50.0	1096.6	0.3
Shrub/Scrub	↑	71.3 (0.05)	6.8	3.9	0.0	40.9	19.8	0.0
Mixed forest		1577.4 (1.1)	171.8	96.2	0.3	884.5	424.6	0.0
Deciduous forest		8967.9 (6.3)	895.6	343.7	0.9	5220.1	2507.5	0.0
Herbaceous		2670.8 (1.9)	394.1	286.6	3.6	704.0	1278.6	3.8
Evergreen forest		145.9 (0.1)	19.8	16.3	0.0	71.1	38.7	0.0
Emergent herbaceous wetlands		1057.0 (0.7)	219.3	5.5	50.7	24.8	754.6	2.1
Hay/Pasture		17,371.4 (12.2)	972.1	985.9	10.5	8838.6	6561.8	2.6
Cultivated crops		100,720.4 (70.5)	5250.6	9690.6	73.8	16,414.9	69,016.4	274.1
Developed, open space		5038.9 (3.5)	350.7	408.5	2.3	1082.3	3185.3	9.9
Developed, medium intensity		686.4 (0.5)	85.7	51.2	0.2	110.6	438.4	0.3
Developed, low intensity		2475.9 (1.7)	187.9	165.8	1.0	614.9	1504.9	1.4
Developed, high intensity	↓	184.8 (0.1)	34.3	9.7	0.0	22.5	118.2	0.0
Barren land	Lower	95.1 (0.1)	33.2	4.9	0.1	11.0	45.9	0.0
Totals		**142,801.0 (100%)**	**9195.7**	**12,080.7**	**148.4**	**34,090.3**	**86,991.2**	**294.7**

Note: Entisols, Inceptisols, Alfisols, Mollisols, and Vertisols are mineral soils. Histosols are mostly organic soils.

3.3. Soil Quality Degradation and Potential Land for Nature-Based Solutions in Iowa

The state of IA experienced extensive SQ degradation from anthropogenic LD with more than 88% of land in the state experiencing anthropogenic LD primarily due to agriculture (93%), followed by developments (6.6%) and barren land (0.1%) (Figure 6, Table 4, Table S5, Figures S2 and S3). All six soil orders were subject to various degrees of anthropogenic LD: Entisols (75%), Inceptisols (94%), Histosols (59%), Alfisols (79%), Mollisols (93%), and Vertisols (98%) (Table 4).

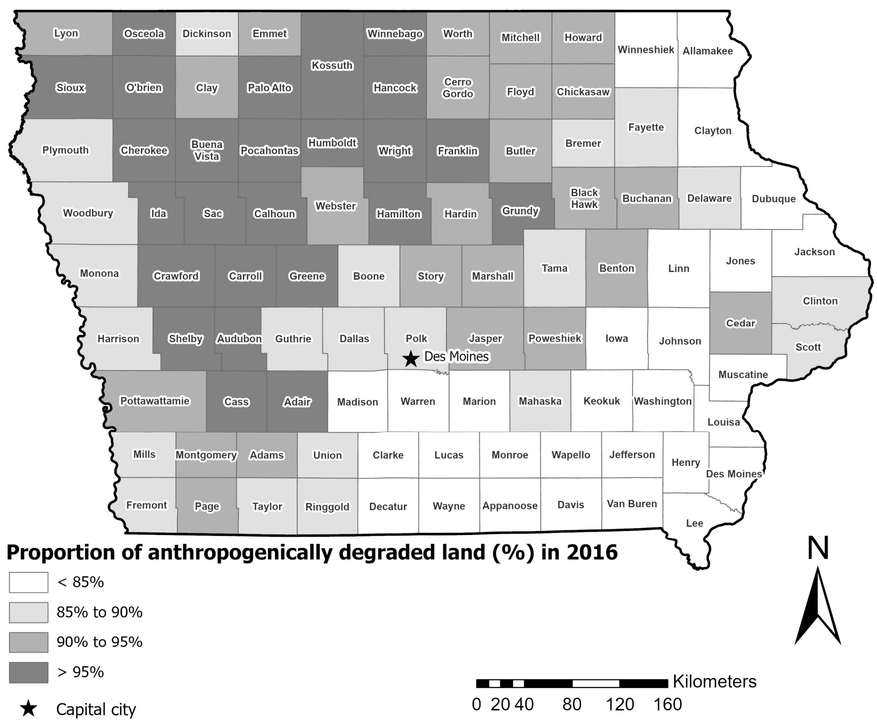


Figure 6. Anthropogenically degraded land proportion (%) by county in the state of Iowa (IA) (USA) in 2016. The proportion of land subject to anthropogenic degradation was calculated as a sum of developed land (developed, open space; developed, high intensity; developed, medium intensity; developed, low intensity), agriculture (cultivated crops, and hay/pasture), and barren land.

The proportion of land considered degraded varied by county from as low as 61% for Allamakee County to as high as 99% for Audubon County (Figure 6). Land degradation was correlated with the average carbon index (CI) [36] of mineral soils for each county (R^2 = 0.72) (Figure 7, Table S5). There was an increased trend in anthropogenic LD from developments in IA overall and all its counties (2001-2016), which indicates a degrading SQ trend over time. Table 5 indicates that all six soil orders experienced LD due to developments and area losses in land cover classes such as woody wetlands, deciduous forest, herbaceous, and hay/pasture. The state of IA has limited land (2.0% of the total state area) that could be used for nature-based solutions (NBS) for SD and LD compensation (Table 4). The potential land for NBS is highly variable by county (Table S5, Figures S4 and S5). Land availability for NBS is also complicated by high private land ownership (97.2%) [37].

Table 4. Status of anthropogenic land degradation (LD) with potential land for nature-based solutions (NBS) by soil order for the state of Iowa (IA) in the United States of America (USA) in 2016. Area changes (percent) from 2001 to 2016 are given in parentheses. Reported values were rounded, which may result in minor discrepancies in calculated sums and percentages.

Soil Order	Total Area		Anthropogenically Degraded Land	Types of Anthropogenic Degradation			Potential Land for Nature-Based Solutions
				Barren	Developed	Agriculture	
	(km^2)	(%)	(km^2)	(km^2)	(km^2)	(km^2)	(km^2)
Slightly Weathered Soils							
	21,425	**15.0**	**18,319 (+0.5)**	**38 (+105.4)**	**1297 (+7.5)**	**16,984 (−0.1)**	**733 (−9.3)**
Entisols	9196	6.4	6914 (+0.4)	33 (+148.1)	659 (+6.0)	6223 (−0.4)	434 (−2.0)
Inceptisols	12,081	8.5	11,317 (+0.6)	5 (−4.6)	635 (+9.2)	10,676 (+0.1)	295 (−18.2)
Histosols	148	0.1	88 (−0.4)	0 (0)	3 (+2.6)	84 (−0.6)	4 (−0.8)
Moderately Weathered Soils							
	121,376	**85.0**	**108,254 (0)**	**57 (+18.8)**	**7089 (+4.5)**	**101,108 (−0.1)**	**2104 (−8.8)**
Alfisols	34,090	23.9	27,095 (+0.3)	11 (+5.5)	1830 (+4.1)	25,254 (0.0)	756 (−9.5)
Mollisols	86,991	60.9	80,871 (+0.1)	46 (+21.9)	5247 (+4.6)	75,578 (−0.2)	1344 (−8.4)
Vertisols	295	0.2	288 (0)	0 (0)	12 (+0.3)	277 (0)	4 (+1.6)
All Soils							
Totals	**142,801**	**100.0**	**126,573 (+0.2)**	**95 (+42.8)**	**8386 (+4.9)**	**118,092 (−0.1)**	**2837 (−8.9)**

Note: Entisols, Inceptisols, Mollisols, Alfisols, and Vertisols are defined as mineral soils. Histosols are mainly organic soils. Anthropogenically degraded land was calculated as a sum of degraded land from agriculture (hay/pasture, and cultivated crops), from development (developed, open space; developed, low intensity; developed, medium intensity; developed, high intensity), and barren land. Developed land includes categories: developed, open space; developed, low intensity; developed, medium intensity; developed, high intensity. Agriculture includes categories: cultivated crops and hay/pasture. Potential land for nature-based solutions (NBS) is limited to herbaceous, shrub/scrub, and barren land cover classes, to provide land areas that would not impact current land uses. Area change was calculated using the following formula: ((2016 Area − 2001 Area)/2001 Area) × 100%.

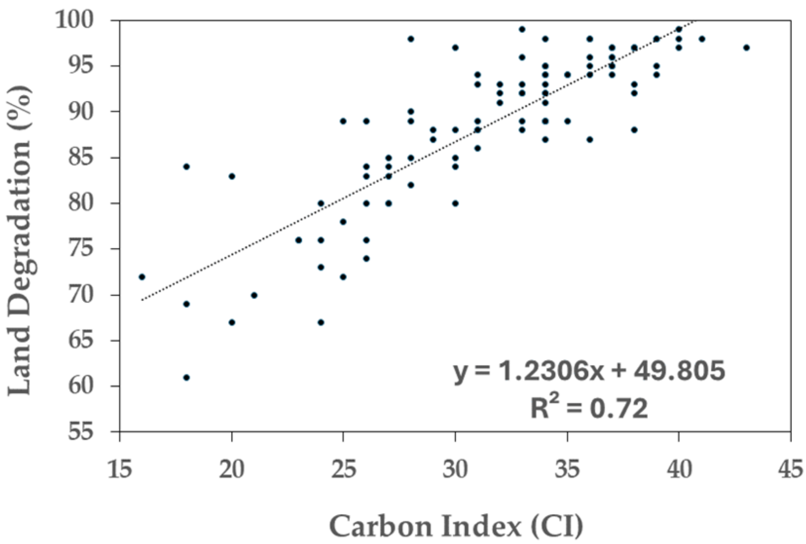


Figure 7. Relationship between the average carbon index (CI) of mineral soils for each county in Iowa [36] and the proportion of land degradation (%) in that county (determined in this study).

Table 5. Changes within the soil quality continuum represented by the land use/land cover (LULC) changes between 2001 and 2016 by soil order for the state of Iowa (IA) (USA).

Soil Quality Continuum									
NLCD Land Cover Classes (LULC), Dynamic Soil Quality (Soil Health Continuum)		**Change in Area, 2001–2016 (%)**	**Inherent Soil Quality (Soil Suitability)**						
			Lower ← → **Higher**						
			Degree of Weathering and Soil Development						
			Slight			**Moderate**			
			Entisols	**Inceptisols**	**Histosols**	**Alfisols**	**Mollisols**	**Vertisols**	
			Change in Area, 2001–2016 (%)						
Woody wetlands	**Higher** ↑	−0.6	−0.5	−0.9	−3.7	−0.7	−0.7	−12.6	
Shrub/Scrub		133.7	403.8	223.5	40.0	106.3	142.7	0.0	
Mixed forest		1.2	0.5	0.9	3.2	1.6	0.8	0.0	
Deciduous forest		−0.6	−1.0	−1.2	−4.0	−0.5	−0.7	−10.9	
Herbaceous		−11.5	−8.0	−19.3	−2.7	−12.5	−10.1	0.9	
Evergreen forest		1.1	−0.5	0.3	0.0	2.0	0.6	0.0	
Emergent herbaceous wetlands		0.0	−3.4	−1.2	3.9	1.8	0.7	−6.7	
Hay/Pasture		−16.6	−12.0	−14.5	−9.7	−17.1	−16.9	−8.6	
Cultivated crops		3.4	2.1	1.9	0.9	12.6	1.8	0.1	
Developed, open space		1.7	1.5	3.5	0.7	2.0	1.5	−0.1	
Developed, medium intensity		28.8	24.1	58.4	13.7	25.3	27.9	9.5	
Developed, low intensity		4.4	3.8	11.1	3.3	3.7	4.1	0.4	
Developed, high intensity		39.4	33.3	84.2	100.0	40.0	38.3	12.2	
Barren land	↓ **Lower**	42.8	148.1	−4.6	118.5	5.5	21.9	127.3	

Note: Inceptisols, Entisols, Alfisols, Mollisols, and Vertisols are mineral soils. Histosols are most often organic soils.

3.4. Soil Quality Damages and Emissions from Iowa Land Development

Despite not having a specific soil health legislation, the Iowa legislature acknowledges the significance of dynamic SQ (soil health) in the management of soil and water resources and calls for the promotion of SH; SH assessments; the inclusion of measures to improve SH in the soil and water conservation planning; the development of comprehensive plans for the soil resources conservation including SH protection and improvement (including changes in land use); the development of methodology to sustain and enhance SH [38]. The accomplishment of these numerous tasks requires SH assessment not only at the field but also at the landscape and state levels. The Iowa legislature is focused on the concept of SH, which is one of the components of the SQ concept. This paper proposes using the two-dimensional concept of an SQ continuum where the inherent capabilities of soil (soil types) and dynamic soil properties (soil health) each represent a dimension.

Our study demonstrates the methodology to quantify the SQ continuum and its changes from LULC changes at various administrative levels and uses soil C, which is an important SH and SQ indicator to quantify TSC losses and associated social costs of emissions (SC-CO_2). The results of our analyses can be presented in various formats (e.g., tables, maps, etc.). This methodology could also be used by Iowa for a cost-benefit analysis of SH conservation. Our study demonstrates the need to extend the soil and water conservation efforts to air conservation as well by limiting GHG emissions from IA soils into the atmosphere, a global common resource. Results from this study provide the following justifications for the above claims:

(1) Damage to soil quality from soil carbon (C) losses and emissions associated with land developments in IA (USA), with a midpoint estimated total of 1.7×10^{11} kg of C losses (Table S6). The highest midpoint soil C losses were in Polk (7.7×10^9 kg C), Linn (4.7×10^9 kg C), and Black Hawk (4.0×10^9 kg C) counties (Figure 8). New development activity between 2001 and 2016 caused a total of 8.0×10^9 kg in C losses. The highest soil C losses were found in Polk (1.5×10^9 kg C), Dallas (6.1×10^8 kg C), and Linn (5.1×10^8 kg C) counties (Table S7, Figure S6). These counties are located adjacent to the Des Moines and Cedar Rapids urban centers.

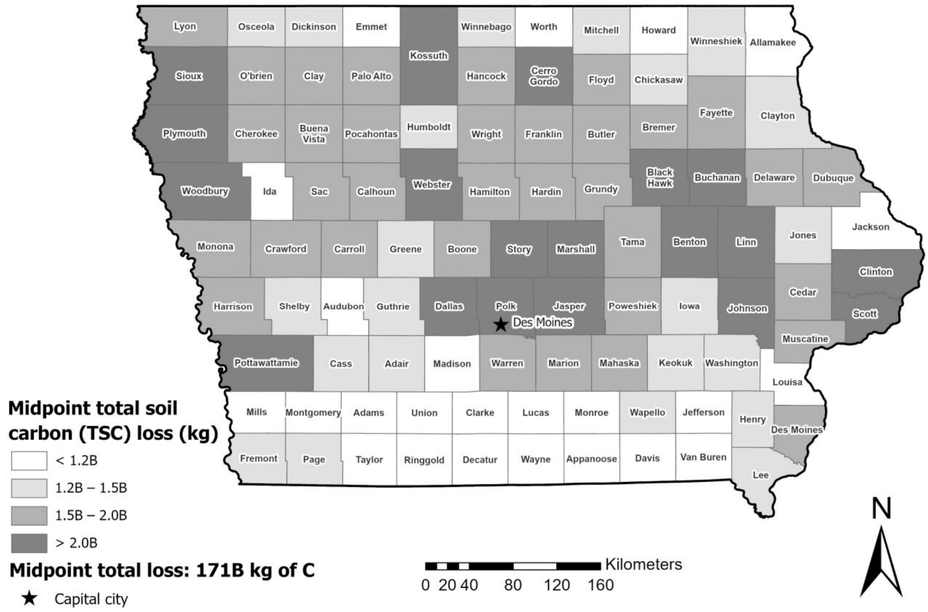


Figure 8. Soil quality (SQ) damage from soil carbon (C) loss with emissions associated with past land developments (through 2016) in Iowa (IA) (USA). Note: B = billion = 10^9.

(2) Damage to soil quality because of loss of land that could potentially be used for soil carbon (C) sequestration because of land development within IA (USA), with 8385.9 km^2 of land area converted to developments before and through 2016 (Figure 9). The largest losses in the area from developments were in the following counties: Polk (369.5 km^2), Linn (238.2 km^2), and Pottawattamie (190.2 km^2) (Figure 9, Table S6). Between 2001 and 2016, new developments caused a total of 398.5 km^2 of conversion to developments (Table S7, Figure S7). The largest area losses from development were found in Polk (75.3 km^2), Dallas (31.8 km^2), and Linn (25.1 km^2) counties (Figure S7). Most developments took place adjacent to Des Moines and Cedar Rapids urban areas and came in place of forest areas and pasture/hay, which are C sequestering land covers compared to developments.

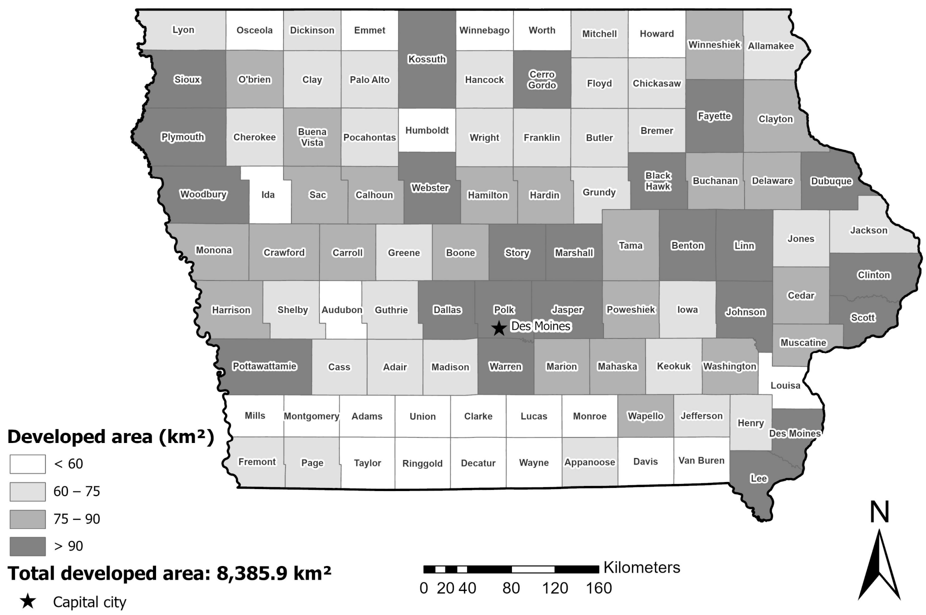


Figure 9. Damages to soil quality (SQ) from the loss of land for potential soil carbon (C) sequestration from past developments (through 2016) in Iowa (IA) (USA).

This study established that recent land developments (2001 and 2016) in IA primarily occurred near already established urban areas. There is a limited amount of potential land (2.0% of the IA area in 2016) that could be used for NBS to potentially repair damages associated with these recent developments (Table 3). The availability of NBS land is further complicated by the high private land ownership (97.2%) [37], intensive agricultural production, and further urbanization [23]. Future urbanization will cause more GHG emissions from soils and further reduce available land for C sequestration. Landscape-level planning can be enhanced by incorporating the concept of social costs of CO_2 (SC-CO_2) emissions to avoid damages to dynamic SQ (soil health). The following section demonstrates the use of this concept in the state of Iowa.

(3) Damage to soil quality from emissions, which can be measured as "realized" social costs of soil carbon (C) (SC-CO_2) released as part of the land development process before and through 2016 in the state of IA (USA), with a total midpoint value of \$28.8B in SC-CO_2 (Figure 10, Table S6). The highest costs were found in Polk (\$1.3B), Linn (\$788M), and Black Hawk (\$677M) counties (Figure 10). From 2001 to 2016, new developments caused a total midpoint value of \$1.3B in SC-CO_2 (Table S7, Figure S8). The highest midpoint costs were found in Polk (\$257.9M), Dallas (\$103.6M), and Linn (\$86.1M) counties (Figure S8).

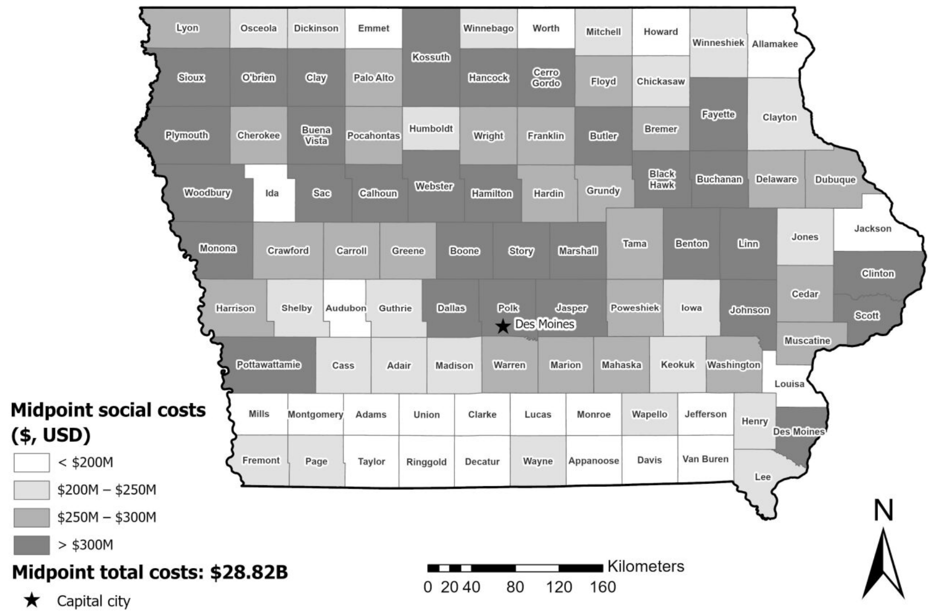


Figure 10. Damage to soil quality (SQ) from emissions can be measured as "realized" social costs of soil carbon (C) (SC-CO_2) from past developments (prior and through 2016) in the state of Iowa (IA) (USA). Note: M = million = 10^6; B = billion = 10^9.

3.5. Soil Quality Damages and Scale Considerations

Changes in land cover, which often impact SQ, can be visualized at multiple spatial scales. High-resolution land cover change analysis at a 30m resolution can show spatial patterns of development and other land cover changes at a high level of detail (Figure 11, Table 6) that could be attributed to parcel-level changes. In the case of Dallas County, IA, there is a high degree of land cover change caused by the encroachment of the City of Des Moines from neighboring Polk County. Nearly all changes in land cover imply disturbance, which is associated with reduced SQ, and the removal of these areas from the potential for agricultural and forestry land uses, as well as any potential for nature-based solutions to improve landscape-level SQ. Increased disturbance has also likely caused the loss of soil C and GHG emissions, and these areas and other hotspots can be noted and tracked over time. With the innovations in satellite remote sensing, it will be possible to track land cover change on nearly a daily basis at less than 1m resolution, allowing for the identification of land uses that increase disturbance.

Dallas County, IA, experienced LULC change between 2001 and 2016, which generated an increase of 31.3 km^2 in developed land categories with an estimated midpoint loss of 1.7×10^9 kg C and a related midpoint loss of \$290.4M of SC-CO_2. There are considerable losses in multiple land cover categories (Table 6), with notable losses in woody wetlands (−1.8%), deciduous forest (−1.2%), emergent herbaceous wetlands (−4.4%), hay/pasture (−15.9%), and cultivated crops (−0.4%) land cover categories. Many of these conversions included agriculturally important soils (e.g., Alfisols and Mollisols).

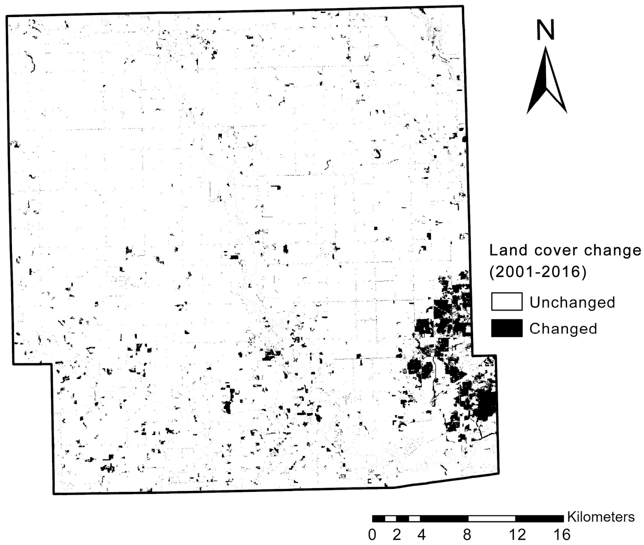


Figure 11. Dallas County, Iowa (IA), USA. Areas that changed land cover between 2001 and 2016 indicate potential damage to soil quality, notably in the area adjacent to the city of Des Moines.

Table 6. Changes within the soil quality continuum represented by the land use/land cover (LULC) changes between 2001 and 2016 shown by soil order for Dallas County, Iowa (IA) (USA).

Soil Quality Continuum								
NLCD Land Cover Classes (LULC), Dynamic Soil Quality (Soil Health Continuum)		**Change in Area, 2001–2016 (%)**	**Inherent Soil Quality (Soil Suitability)**					
			Lower ←				→	**Higher**
			Degree of Weathering and Soil Development					
			Slight			**Moderate**		
			Entisols	**Inceptisols**	**Histosols**	**Alfisols**	**Mollisols**	**Vertisols**
			Change in Area, 2001–2016 (%)					
Woody wetlands	**Higher**	−1.8	0.0	−2.0	0.0	−3.4	−1.8	0.0
Shrub/Scrub	↑	183.7	0.0	4.5	0.0	255.0	325.0	0.0
Mixed forest		0.7	0.0	−0.1	0.0	1.4	0.4	0.0
Deciduous forest		−1.2	−3.7	−0.8	0.0	−1.0	−1.9	0.0
Herbaceous		0.2	−11.6	−4.4	0.0	−3.1	5.2	0.0
Evergreen forest		8.2	0.0	2.7	0.0	7.4	14.3	0.0
Emergent herbaceous wetlands		−4.4	0.0	0.0	0.0	8.3	−4.4	0.0
Hay/Pasture		−15.9	−25.6	−20.9	0.0	−9.9	−17.0	0.0
Cultivated crops		−0.4	2.1	−0.6	0.0	6.4	−0.8	0.0
Developed, open space		11.7	1.0	14.8	0.0	10.5	10.3	0.0
Developed, medium intensity		132.6	25.8	171.8	0.0	178.3	116.3	0.0
Developed, low intensity		33.6	8.3	48.5	0.0	24.3	28.1	0.0
Developed, high intensity	↓	174.7	55.8	160.1	0.0	1252.0	165.2	0.0
Barren land	**Lower**	−1.3	−10.0	−22.6	0.0	−10.7	6.4	0.0

Note: Entisols, Inceptisols, Alfisols, Mollisols, and Vertisols are mineral soils. Histosols are predominately organic soils.

4. Discussion

4.1. Redefining Soil Quality at the Landscape Level: The Soil Quality Continuum

Soil quality is typically considered at the field scale [25], which combines the concepts of inherent SQ represented by soil type with dynamic SQ, which equates to soil health. This paper proposes complementing the widely researched topic of soil health with the concept of SQ continuum which encompasses both the inherent capabilities of soil as well as soil health (Table 7). This SQ continuum concept is two-dimensional, with soil health and inherent soil properties, each having a dimension that is critical to our understanding of soil resources and their change over time (Table 7). Another limitation of both the concepts of soil health and SQ is that they are typically seen as relevant in terms of agriculture soil and crop practices using fields as the unit of study [25]. The dynamic SQ (soil health) is often understood in terms of disturbance regimes, where continuous plowing and limited plant inputs to the soil are seen as the most degrading, while pasture or limited-till agriculture has the potential to aggrade SQ and soil health [25]. While the concept of SQ continuum is useful at the field scale in agronomic systems, it neglects the landscape-level view of soil resources and the overall conservation of these resources. This is important because there can be non-agronomic activities (e.g., development) that cause volatilization of soil C and the essential removal of soil resources from the landscape, as well as land cover types outside of agricultural uses that still contain vital soil resources. It is critical to first understand the inherent soil properties at the landscape level through the soil types present because these soil types have well-defined capabilities to support agriculture and other uses, as well as levels of soil C, which can serve as a reservoir or source of potential GHG emissions. When this soil information is combined with satellite-based land cover change analysis, it is possible to identify disturbance regimes, as well as locations of new human development. Future efforts and technological advances will allow for more refined tracking of disturbance and should also include physical measurement and monitoring of soils throughout the landscape.

Table 7. A newly proposed concept showing that the soil quality continuum is both influenced by inherent soil quality (soil suitability) (e.g., soil type with an example given from the soil types found in the state of Iowa, IA, USA) and dynamic soil quality (soil health continuum) based on land cover type. The lower end of the soil quality continuum corresponds to a higher degree of disturbance (developed land classes) or limited soil function (barren land), compared to higher soil quality in limited soil disturbance land classes (e.g., wetlands, etc.) (adapted from Karlen et al. (2019) [25]).

Soil Quality Continuum							
NLCD Land Cover Classes (LULC), Dynamic Soil Quality (Soil Health Continuum)		Inherent Soil Quality (Soil Suitability)					
		Lower ← → Higher					
		Degree of Weathering and Soil Development					
		Slight			Moderate		
		Entisols	Inceptisols	Histosols	Alfisols	Mollisols	Vertisols
Woody wetlands	Higher	Higher	Higher	Higher	Higher	Higher	Higher
Shrub/Scrub							
Mixed forest							
Deciduous forest							
Herbaceous							
Evergreen forest							
Emergent herbaceous wetlands							
Hay/Pasture							
Cultivated crops							
Developed, open space							
Developed, medium intensity							
Developed, low intensity							
Developed, high intensity							
Barren land	Lower	Lower	Lower	Lower	Lower	Lower	Lower

4.2. Study Implications in a Broader Context

4.2.1. Significance of the Results for Iowa's Pending Soil Health Legislation

Iowa is currently considering legislation related to the management of soil and water resources, which includes soil health (HL282 https://www.legis.iowa.gov/legislation/BillBook?ga=90&ba=HF282 (accessed on 9 March 2024) [39]. This proposed legislation recommends financial assistance for activities that improve soil health and reduce erosion, which would serve to reduce SQ degradation. This includes specific mention of providing incentives to landowners who use agricultural practices that can improve soil health and limit soil erosion (e.g., no-till planting, use of cover crops, etc.). The bill under consideration would also direct the development and publishing of comprehensive plans for the conservation of soil health resources and improvement of soil health by providing specific recommendations on best practices. Additionally, the legislation would mandate the assessment of soil conditions for the state of IA and suggest the development of methods to maintain and improve soil health. Finally, the legislation under consideration suggests that information on practices that improve soil health be incorporated into instruction through collaboration with school districts. This proposed legislation does not mention or discuss soil C and the related GHG emissions that can be associated with SQ degradation. Our study provides geospatial methodology and data to enrich Iowa's pending soil health legislation with landscape-level analysis of soil health and complement other studies in the state [38].

4.2.2. Significance of the Results for Iowa's Climate Change

Despite ongoing climate change impacts on IA, there are no finalized state-led climate change preparation and adaptation plans (https://www.georgetownclimate.org/adaptation/plans.html (accessed on 9 March 2024) [40]. Iowa has been experiencing a magnitude of impacts from climate change: rising atmospheric temperatures and precipitation, increased flooding frequency, crop failure because of weather extremes, droughts, and many others [41]. Vahedifard et al. (2024) [42] warned of an "amplifying feedback loop between drought, soil desiccation cracking, and GHG emissions." Climate change is particularly dangerous to SQ and agriculture in IA, which is a "Corn Belt" state producing over 50% of all US soybeans (sp. Glycine mas) and corn (sp. Zea mays) using highly mechanized and chemically intensive methods [43,44]. Results of our study show that SQ degradation from land conversions in IA resulted in GHG emissions from agriculture and development, which can be quantified and monitored using geospatial techniques. These GHG emissions extend beyond the boundaries of the state of IA and need to be accounted for (e.g., "polluter-pays-principle" [45], etc.) in the global loss and damage (L&D) finance.

4.2.3. Significance of Iowa's Results for the United Nations (UN) Sustainable Development Goals (SDGs) and Other UN Initiatives

Since Iowa is one of the many states within the United States of America, the study results are important for the United Nations (UN) Sustainable Development Goals (SDGs), which were adopted in 2015 [46], and other UN initiatives (e.g., UN Convention to Combat Desertification [47]; UN Convention on Biological Diversity [48]; UN Kunming-Montreal Global Biodiversity Framework [49]). Mikhailova et al. (2023, 2024) [50,51] found that it is important to evaluate individual administrative areas when considering soil relationship to UN SDGs and other UN initiatives, because of the variability that is masked when states are aggregated into one unit for analysis (e.g., country). Our study found reported results relevant to the UN initiatives for the following reasons:

- For the state of IA, there was a reduction in the amount of land under the hay/pasture land cover between 2001 and 2016 across all soil orders (Table 3). Given this loss of agriculturally relevant land uses, there was less capacity for production in these areas (which addresses *UN SDG 2: Zero Hunger*);

- Newly developed land in IA took place in areas with each of the six soil orders, including soils that are considered the most agriculturally vital (e.g., Mollisols, Alfisols) and also with Histosol soils with high levels of C (Table 3, addressing *UN SDG 12: Responsible Consumption and Production*);
- The state of IA has not finalized state-led climate change preparation and adaptation plans (https://www.georgetownclimate.org/adaptation/plans.html (accessed on 9 March 2024) [40]. Agriculture and land development in IA has caused damage to dynamic SQ (soil health) from the loss of soil C and the subsequent emission of carbon dioxide (CO_2). All land developments in IA can be linked to damages to SQ, with 8,385.9 km^2 developed, resulting in midpoint losses of 1.7×10^{11} kg of total soil carbon (TSC) and a midpoint social cost of carbon dioxide emissions (SC-CO_2) of $28.8B (where B = billion = 10^9, USD). More recently developed land area (398.5 km^2) between 2001 and 2016 likely caused the midpoint loss of 8.0×10^9 kg of TSC and a corresponding midpoint of $1.3B in SC-$CO_2$. Data on variability associated with these estimates are presented in the Supplemental Materials of this article. There is only a small amount of potential land (2.0% of the total land area) that can be used for nature-based solutions to SQ degradation and C sequestration (addressing *UN SDG 13: Climate Action*);
- The state of IA was not land degradation neutral (LDN), with more than 88% of land in IA experiencing anthropogenic LD primarily due to agriculture (93%). All six soil orders were subject to various degrees of anthropogenic LD: Entisols (75%), Inceptisols (94%), Histosols (59%), Alfisols (79%), Mollisols (93%), and Vertisols (98%). Soil and LD have primarily increased between 2001 and 2016, especially in the developed LD type. Development has reduced overall soil resources from land cover change between 2001 and 2016 for all 99 counties in IA (Table 3, Table S5). There were cutbacks in the total areas of woody wetlands, deciduous forests, and herbaceous land covers, which reduced C sinks, therefore increasing GHG emissions and other pollutants to the atmosphere (Table 3) (addressing *UN SDG 15: Life on Land; UN Convention to Combat Desertification; UN Convention on Biological Diversity; UN Kunming-Montreal Global Biodiversity Framework*);
- Goals of the recent *UN Kunming-Montreal Global Biodiversity Framework* [49] include a focus on the resilience and integrity of all ecosystems (Goal A: "*The integrity, connectivity and resilience of all ecosystems are maintained, enhanced, or restored, substantially increasing the area of natural ecosystems by 2050*"), with a target to preserve and enhance ecosystem functions and services, including soil health-related contributions (Target 11: "*Restore, maintain and enhance nature's contributions to people, including ecosystem functions and services, such as regulation of air, water, and climate, soil health*. . ." This study found a loss of soil diversity (pedodiversity) from land developments, which reduced the available soil resources and associated biodiversity. Furthermore, our study supports Target 21, which discusses using the best data to guide decision-making (Target 21: "*Ensure that the best available data, information and knowledge, are accessible to decision makers, practitioners and the public to guide effective and equitable governance*. . .") given our analysis is based on publicly available soil data and satellite-derived land cover information analyzed in a spatial context to more readily support analysis and policy-making to reach the biodiversity goals.

5. Conclusions

The reason that SQ evaluation is so important is that it can be used to evaluate both the inherent soil qualities and the variable soil health. In that way, SQ can be used to first target the most productive and often most vulnerable soils within a landscape while also tracking the overall LD of the soils through analysis of land cover use and change. This paper proposes using the two-dimensional concept of SQ continuum where the inherent capabilities of soil (soil types) and dynamic soil properties (soil health) each represent a dimension. Both the soil health and SQ concepts have primarily focused on field-scale agronomic evaluation and monitoring, which is important but does not consider the soil resources available at the landscape level. Expanding the monitoring of soil resources across agronomic, forestry, and urban areas using SQ-related evaluation improves our understanding of how these resources change over time and also helps identify consumptive uses of soil that can cause GHG emissions and reduce the ecosystem resources that soils can provide. Reduction in overall SQ equates to losses and damages (L&D), which should be understood and addressed through land conservation and soil health efforts. While IA has large areas of highly fertile soils (Alfisols, Mollisols), the SQ continuum in IA has been impacted by long-term agronomic practices and development (71% cultivated crops and 6% developed) compared to the U.S. soil health continuum (20% cultivated crops and 6% developed) in the contiguous U.S. Although this study used soil order level analysis, it can also be used at any other Soil Taxonomic level for more detailed results.

Soil health-related legislation is currently under consideration in IA [38] and includes recommendations to incentivize agricultural practices that improve soil health, as well as surveys to understand soil health resources. The legislation recommends developing comprehensive plans linked to recommended best practices to improve soil health but does not mention or include the conservation of soil C in relation to climate change. Given our findings, IA legislators may consider the inclusion of climate-change-related considerations. With IA subject to many climate change-related losses while serving as a critical food production state, it is important to consider how land management decisions impact soil C and GHG emissions that are linked to climate change.

This study's results are relevant to the United Nations (UN) Sustainable Development Goals (SDGs) and other UN initiatives. Overall, the state of IA has lost hay/pasture land while having increased developments on agriculturally vital soils. With the nearly ubiquitous agriculture, combined with losses from land development, the soil resources in IA are not land degradation or SQ degradation neutral, as they have degraded over years of human activity. It is important to note that SQ is a process that changes over time, with changes starting with indigenous land management and greatly impacted by conversions of prairies to agriculture uses in IA. Much of these changes occurred before the advent of remote sensing technology, so much of the SQ degradation occurred before it could be tracked. When examining SQ, it is important to determine a baseline and goals, for example, is the goal to increase SQ to prairie levels, or is the goal to prevent further SQ degradation, while maintaining agricultural productivity. Geospatial technologies offer opportunities for rapid and regular monitoring of SQ over large geographic areas. Future research could develop estimates of C losses and associated social costs linked to agricultural activities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13040547/s1, Table S1. Soil diversity (pedodiversity) is expressed as taxonomic diversity at the level of soil order in the state of Iowa (IA) (USA); Table S2. An overview of the accounting framework used by this study (adapted from Groshans et al. (2019) [26]) for the state of Iowa (IA) (USA); Table S3. Area-normalized content (kg m^{-2}) and monetary values ($ m^{-2}) of soil organic carbon (SOC), soil inorganic carbon (SIC), and total soil carbon (TSC = SOC + SIC) by soil order using data developed by Guo et al. (2006) [29] for the upper 2-m of soil and an avoided social cost of carbon (SC-CO_2) of $46 per metric ton of CO_2, applicable for 2025 (2007 U.S. dollars with an average discount rate of 3% [27]); Table S4. Distribution of soil carbon regulating ecosystem services in the state of Iowa (IA) (USA) by soil order; Table S5. Anthropogenic land degradation status and potential land for nature-based solutions in the state of Iowa (IA) in the contiguous United States of America (USA) in 2016. Percent changes in area from 2001 to 2016 are shown in parentheses. Reported values have been rounded; therefore, calculated sums and percentages may exhibit minor discrepancies. This table shows the anthropogenic land degradation status in 2016 but most likely does not account for historical anthropogenic land degradation as well as most of the inherent land degradation; Table S6. Developed land and potential for realized social costs of carbon (C) due to complete loss of total soil carbon (TSC) of developed land by soil order in the state of Iowa (IA) (USA) prior and through 2016; Table S7. Increases in developed land and potential for realized social costs of carbon (C) due to complete loss of total soil carbon (TSC) of developed land by soil order in the state of Iowa (IA) (USA) from 2001 to 2016; Figure S1. High-resolution aerial photos showing examples of land classes (LULC) which were used to determine anthropogenically degraded land (LD) in the state of Iowa (IA) (USA) by assuming that degraded lands are represented by the land classes (LULC) for agriculture (hay/pasture, and cultivated crops), development (developed, open space; developed, low intensity; developed, medium intensity; developed, high intensity) and barren lands. Representative examples were located using a land cover map of the contiguous United States of America (USA) for 2016 (based on data from the Multi-Resolution Land Characteristics Consortium (MRLC) with detailed descriptions of the land classes [30]); Figure S2. Anthropogenic land degradation status is presented as the total degraded land area (km^2) in the state of Iowa (IA) (USA) in 2016. Anthropogenically degraded land was calculated as a sum of degraded land from agriculture (hay/pasture, and cultivated crops), from development (developed, open space; developed, low intensity; developed, medium intensity; developed, high intensity), and barren land; Figure S3. Change in anthropogenic land degradation status is presented as the total degraded land area (km^2) over time (2001–2016) by county in the state of Iowa (IA) (USA). Anthropogenically degraded land was calculated as a sum of degraded land from agriculture (hay/pasture, and cultivated crops), from development (developed, open space; developed, low intensity; developed, medium intensity; developed, high intensity), and barren land; Figure S4. The status of potential land for nature-based solutions (NBS) is presented as the proportion of potential NBS land over the total land area (%) by county in the state of Iowa (IA) (USA). Potential land for NBS is limited to barren land, shrub/scrub, and herbaceous land cover classes, to provide potential land areas without impacting current land uses; Figure S5. Change in the status of potential land area for nature-based solutions (NBS) (km^2) over time (2001–2016) by county in the state of Iowa (IA) (USA). Potential land for NBS is limited to barren land, shrub/scrub, and herbaceous land cover classes, to provide potential land areas without impacting current land uses; Figure S6. Damage to soil quality because of soil carbon (C) loss with associated emissions from more recent land developments between 2001 and 2016 in Iowa (IA) (USA). Note: M = million = 10^6, B = billion = 10^9; Figure S7. Damages to soil quality because of loss of land for potential soil carbon (C) sequestration from land developments that occurred between 2001 and 2016 for Iowa (IA) (USA); Figure S8. Damage to soil quality (SQ) from emissions can be measured as "realized" social costs of soil carbon (C) (SC-CO_2) from recent land developments in the state of Iowa (IA) (USA) from 2001 to 2016. Note: M = million = 10^6, B = billion = 10^9.

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Glossary

B	Billion
BS	Base saturation
CF	Carbon footprint
CCA	Climate Change Adaptation
CO_2	Carbon dioxide
EPA	Environmental Protection Agency
GHG	Greenhouse Gases
IA	Iowa
LD	Land degradation
LDN	Land degradation neutrality
L&D	Loss and damage
LULC	Land use/land cover

LULCC	Land use/land cover change
M	Million
MRLC	Multi-Resolution Land Characteristics Consortium
N	North
NBS	Nature-based solutions
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
SC-CO_2	Social cost of carbon emissions
SD	Soil degradation
SDGs	Sustainable Development Goals
SH	Soil health
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
SQ	Soil quality
SQC	Soil quality continuum
SQI	Soil quality indicator
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
TSC	Total soil carbon
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
USDA	United States Department of Agriculture
W	West

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