Contribution of Land Cover Conversions to Connecticut (USA) Carbon Footprint

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Abstract: Greenhouse gas (GHG) emissions from landcover conversions contribute to the total carbon (C) footprint (CF), which is the sum of GHG emissions from various sources and events expressed as carbon dioxide (CO$_2$) equivalent. Soil-based emissions from land conversions are often excluded from the total CF, which can lead to underreporting the CF. This study uses the state of Connecticut (CT) as a case study to demonstrate the importance of soil-based emissions from land cover conversions to the state’s CF. The state of CT Public Act 08-98 (2008): Global Warming Solutions Act (GWSA) set a statutory requirement to cut GHG emissions 10 percent below 1990 levels by 2020 and 80 percent below 2001 levels by 2050 without considering soil-based emissions from land conversions. This omission results in underestimates of past and current emissions related to CT’s CF. In addition, not accounting for soil-based emissions from land conversions may increase the future size of CT’s CF. Remote sensing and soil data analysis provide an opportunity for rapid, quantitative, and temporal assessment of the contribution of land cover conversions to CT’s CF by soil type, land cover type, and administrative units (counties). Results are reported for soil organic carbon (SOC), soil inorganic carbon (SIC), and total soil carbon (TSC) based on C contents and monetary values of social costs of carbon. The state of CT experienced soil-based emissions from land cover conversions from 2001 to 2016 with $388.1M (where $ = USD, M = million = 10^6) worth of “realized” social costs of carbon dioxide (SC-CO$_2$) emissions which should be accounted for in CT’s total CF. The current methodology could be used to optimize future land conversions to minimize the amount of soil GHG emissions by considering the soil C resources in different development scenarios. With an extensive, densely populated coastal area, CT will be directly affected by rising sea levels and other climate change impacts. Future research can focus on owner-specific CF contributions to address the responsibility for costs of GHG emissions as well as limiting the CF impact of land conversions.

Keywords: emissions; CO$_2$; climate change; damage; evidence; law; risk; sea rise; sprawl

1. Introduction

Carbon footprint is increasingly being used to analyze GHG emissions, but the term “carbon footprint” can be difficult to define because it has a wide range of applications [1–3]. The carbon footprint was inspired by the “ecological footprint,” which refers to the biologically productive sea and land area (so-called global hectares) needed to support a given...
population [4]. In general, CF is defined as GHG emissions from various sources and events expressed as carbon dioxide (CO$_2$) equivalent [2]. The concept of CF, in some instances, became a commercialized tool for estimating GHG emissions and using these estimates for emission reductions, disclosures, comparisons, business transactions, and many other uses [2]. Carbon footprint estimation is a three-step process that involves the selection of GHG, boundary setting, and GHG emission data gathering [2]. Applications of CF to soils, land covers, and land uses have been somewhat limited because of the complex nature of soils and the ecosystem goods and services (provisioning, regulating, and cultural) they provide to human society [5–9]. The concept of CF fits particularly well with the regulating ecosystem services (e.g., gas regulation, carbon sequestration, etc.) provided by soils, which can be valued based on the concept of social costs of carbon emissions [10,11]. The concept of CF is important in climate change preparations and planning [12], but CF from soil-based emissions from land conversions is often overlooked in GHG inventories and plans.

This study proposes a practical method of identifying the soil-based emissions CF over time by using remote sensing analysis to locate areas with land disturbances and link them to soil types that have characteristic soil carbon contents. Then, the soil CF is determined by using the area of land disturbance and soil carbon content to calculate the maximum potential for realized social costs of C (SC-CO$_2$) from each disturbance (Figure 1). These estimates can be performed at various administrative and spatial scales (Figure 1).

Figure 1. The soil “carbon footprint” concept is an intersection between soil storage by soil type and land cover classes under natural or anthropogenic disturbance (adapted from Bétard and Peulvast 2019 [13]; Mikhailova et al. 2021 [14]), which can be estimated using various scales and time periods for a cost-effective mitigation policy.

The Role of Soils in Connecticut’s Global Warming Solutions Act and Carbon Footprint

The state of CT is experiencing various effects of climate change (e.g., increasing temperatures, changing precipitation patterns, sea-level rise, etc.) [15]. The state of CT GWSA (PA 08-98) (2008) set a statutory requirement to cut GHG emissions 10 percent below 1990 levels by 2020 and 80 percent below 2001 levels by 2050 without considering soil-based emissions from land conversions [16]. This omission leads to an underestimate of the past and current CT’s CF. In addition, not accounting for soil-based emissions from land conversions may increase the future size of CT’s CF.

Pedodiversity (soil diversity) of CT defines the soil regulating ecosystem services and disservices (ES/ED) and the potential ability of soils to store (C sequestration as ES) or release CO$_2$ (carbon footprint as a ED) (Table 1, Figure 2). Soils of CT have undergone varying degrees of weathering: slightly weathered (Entisols, Inceptisols, Histosols) and moderately weathered (Mollisols) soils (Table 1, Figure 2). Entisols (13% of the total area) and Inceptisols (84% of the total area) contain low soil C contents with limited capacity to sequester C because of their slight degree of weathering and soil development [17]. Histosols (2% of the total area) can contain remarkable quantities of SOC and are commonly
found in CT’s wetlands [17]. Mollisols (1% of the total area) are fertile soils but rarely seen in the state. Connecticut selected Entisols to be the State Soil (soil series name: Windsor) for its importance in the production of shade tobacco, fruit, vegetables, corn for silage, and ornamental trees and shrubs [18].

The state of CT has undergone considerable land cover change since the 1700s, accompanied by deforestation, cropland, and pasture expansion, with up to 60–80 percent of the land being deforested by the mid-1800s [19]. These past events most likely caused significant ecological and carbon losses, which contributed to the ecological and carbon debts [20]. By the 1990s, however, much of the land was reverted to forest cover [19]. Currently, the state of CT is experiencing land cover changes associated with developments with potential ecological and carbon losses, which are challenging to assess [19,21,22]. The state has high private land ownership, with 93.8% of the land privately owned [23].

Table 1. Soil diversity (pedodiversity) is expressed as taxonomic diversity at the level of soil order and ecosystem service types in Connecticut (U.S.A.) (adapted from Mikhailova et al., 2021 [11]).

| Stocks | Ecosystem Services |
|--------|-------------------|
| Soil Order | General Characteristics and Constraints | Provisioning | Regulation/Maintenance | Cultural |
| Slightly Weathered |
| 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 |
| Moderately Weathered |
| Mollisols | Carbon-enriched soils with B.S. ≥ 50% | x | x | x |

Note: B.S. = base saturation.

Figure 2. General soil map of Connecticut (U.S.A.) (Latitude: 40°58’ N to 42°03’ N; Longitude: 71°47’ W to 73°44’ W) derived from the SSURGO database [24] overlaid with county boundaries [25].

Previous research on the impact of land-use change on GHG inventories and state-level climate mitigation policy in CT used InVEST model methodologies for estimating soil carbon pools in the state by determining a C pool size for each land cover class, ignoring
the wealth of soil spatial data available [21]. Therefore, for any specific land cover class (e.g., forests), one value for soil C was assumed across the landscape for that land cover type [21]. This method is limited because of the greatly simplified assumption of only one value of C content per land cover class because land cover classes can contain multiple soil types with different soil C contents.

This study proposes a different methodology for soil C inventory that uses soil spatial data to estimate soil C storage for CT based on soil C content by soil order because soil orders typically have various soil C contents. These various soil C contents are used to represent soil C variability within each individual land cover. Soil-based emissions (CF) from land conversions are the emissions from soil orders within newly developed areas (CO₂ release = newly developed area by soil order x soil order C content). The hypothesis of this study is that soil CF can be determined by utilizing satellite image analysis to identify newly developed areas of land disturbance integrated with soil spatial databases to estimate the soil CF.

The specific objective of this study was to assess the value of SOC, SIC, and TSC in the state of CT (USA) and its change in the past 15 years (CF) based on the social cost of carbon (SC-CO₂) and avoided emissions provided by carbon sequestration, which the U.S. Environmental Protection Agency (EPA) has determined to be $46 per metric ton of CO₂, applicable for the year 2025 based on 2007 U.S. dollars and an average discount rate of 3% [10]. Our calculations provide estimates for the monetary values of SOC, SIC, and TSC across the state and by different spatial aggregation levels (i.e., county) using information previously reported by Guo et al. (2006) [26] based on the State Soil Geographic (STATSGO) database. Soil order areas were obtained from the Soil Survey Geographic Database (SSURGO) [24]. Classified land cover data for 2001 and 2016 were downloaded from the Multi-Resolution Land Characteristics Consortium (MRLC) website [27].

2. Materials and Methods

This study used both biophysical (science-based, Figure 2) and administrative (boundary-based, Figure 2) accounts to calculate monetary values for SOC, SIC, and TSC (Tables 2 and 3). Table 2 was enhanced by the addition of carbon footprint next to the “realized social” social cost of carbon (SC-CO₂) emissions in the “value” column.

Table 2. A conceptual overview of the accounting framework for carbon footprint (CF), which was used in this study (adapted from Groshans et al. (2019) [28]) for the state of Connecticut (USA).

| Ownership (e.g., government, private, foreign, shared, single, etc.) | Stocks/Source Attribution | Flows | Value |
|---|---|---|---|
| Time (e.g., information disclosure, etc.) | Biophysical Accounts (Science-Based) | Administrative Accounts (Boundary-Based) | Monetary Account(s) | Benefit(s) | Total Value |
| Soil extent: | Administrative extent: | Ecosystem good(s) and service(s): | Sector: | Types of value: |
| Composite (total) stock: Total soil carbon (TSC) = Soil organic carbon (SOC) + Soil inorganic carbon (SIC) |
| Past (e.g., post-development disclosures) | - Soil orders (Entisols, Inceptisols, Histosols, Mollisols) | - State (Connecticut) | Environment |
| Current (e.g., status) | - - County (8 counties) | - Regulating (e.g., carbon sequestration) | - Carbon sequestration |
| Future (e.g., pre-development disclosures) | - $46 per metric ton of CO₂ applicable for 2025 (2007 U.S. dollars with an average discount rate of 3% [10]) | | | |
Table 3. Soil diversity (pedodiversity) by soil order (taxonomic pedodiversity) and county in Connecticut (U.S.A.) based on Soil Survey Geographic (SSURGO) Database (2020) [11].

| County    | Total Area (km²) (%) | Degree of Weathering and Soil Development |
|-----------|----------------------|------------------------------------------|
|           |                      | Slight Entisols | Inceptisols | Histosols | Mollisols |
|           |                      | 2016 Area (km²), (% of Total County Area) |
| Fairfield | 1557.8 (13)          | 211.0 (14)     | 1316.7 (85) | 28.1 (2)  | 2.1 (0)   |
| Hartford  | 1840.8 (15)          | 520.0 (28)     | 1293.0 (70) | 14.1 (1)  | 13.7 (1)  |
| Litchfield| 2317.3 (19)          | 122.0 (5)      | 2121.3 (92) | 62.3 (3)  | 9.8 (0)   |
| Middlesex | 935.7 (8)            | 88.6 (9)       | 821.6 (88)  | 22.1 (2)  | 3.4 (0)   |
| New Haven | 1491.8 (12)          | 250.8 (17)     | 1191.7 (80) | 36.6 (2)  | 12.7 (1)  |
| New London| 1706.2 (14)          | 158.3 (9)      | 1502.5 (88) | 45.5 (3)  | 0         |
| Tolland  | 1029.8 (8)           | 101.7 (10)     | 912.5 (89)  | 11.6 (1)  | 3.9 (0)   |
| Windham  | 1308.0 (11)          | 173.6 (13)     | 1099.0 (84) | 35.5 (3)  | 0         |
| Totals   | 12,187.5 (100)       | 1626.0 (13)    | 10,260.1 (84)| 255.8 (2) | 45.6 (1)  |

Table 4 presents area-normalized contents (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 based on data reported by Guo et al. (2006) [26] for the upper 2 m of soil and an avoided social cost of carbon (SC-CO₂) of $46 per metric ton of CO₂, applicable for 2025 (2007 U.S. dollars with an average discount rate of 3% [10]).

Table 4. 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 based on data reported by Guo et al. (2006) [26] for the upper 2 m of soil and an avoided social cost of carbon (SC-CO₂) of $46 per metric ton of CO₂, applicable for 2025 (2007 U.S. dollars with an average discount rate of 3% [10]).

| Soil Order | SOC Content | SIC Content | TSC Content | SOC Value | SIC Value | TSC Value |
|------------|-------------|-------------|-------------|-----------|-----------|-----------|
|             | Minimum—Midpoint—Maximum Values | Midpoint Values |
|             | (kg m⁻²) | (kg m⁻²) | (kg m⁻²) | ($ m⁻²) | ($ m⁻²) | ($ m⁻²) |
| Slightly Weathered |
| Entisols   | 1.8–8.0–15.8 | 1.9–4.8–8.4 | 3.7–12.8–24.2 | 1.35 | 0.82 | 2.17 |
| Inceptisols| 2.8–8.9–17.4 | 2.5–5.1–8.4 | 5.3–14.0–25.8 | 1.50 | 0.86 | 2.36 |
| Histosols  | 63.9–140.1–243.9 | 0.6–2.4–5.0 | 64.5–142.5–248.9 | 23.62 | 0.41 | 24.03 |
| Moderately Weathered |
| Mollisols  | 5.9–13.5–22.8 | 4.9–11.5–19.7 | 10.8–25.0–42.5 | 2.28 | 1.93 | 4.21 |
Land use/land cover change in CT between 2001 and 2016 was analyzed using classified land cover data from the Multi-Resolution Land Characteristics Consortium (MRLC) [27]. Changes in land cover, with their associated soil types, were calculated in ArcGIS Pro 2.6 [29] by comparing the 2001 and 2016 data, converting the land cover to vector format, and unioning the data with the soils layer in the Soil Survey Geographic (SSURGO) Database [24].

Table 5. Midpoint soil organic carbon (SOC) storage by soil order and county for the state of Connecticut (USA), based on the areas shown in Table 3 and the midpoint SOC contents in Table 4.

| County       | Total SOC Storage (kg) (%) | Degree of Weathering and Soil Development |
|--------------|---------------------------|------------------------------------------|
|              |                           | Slight (kg) | Moderate (kg) |
|              |                           | Entisols | Inceptisols | Histosols | Mollisols |
| Fairfield    | $1.7 \times 10^{10}$ (12) | $1.7 \times 10^{9}$ (10) | $1.2 \times 10^{10}$ (67) | $3.9 \times 10^{8}$ (23) | $2.8 \times 10^{8}$ (0) |
| Hartford     | $1.8 \times 10^{10}$ (13) | $4.2 \times 10^{9}$ (23) | $1.2 \times 10^{10}$ (65) | $2.0 \times 10^{8}$ (11) | $1.8 \times 10^{8}$ (1) |
| Litchfield   | $2.9 \times 10^{10}$ (20) | $9.8 \times 10^{8}$ (3) | $1.9 \times 10^{10}$ (66) | $8.7 \times 10^{8}$ (30) | $1.3 \times 10^{8}$ (1) |
| Middlesex    | $1.1 \times 10^{10}$ (8)  | $7.1 \times 10^{8}$ (6) | $7.3 \times 10^{8}$ (65) | $3.1 \times 10^{8}$ (28) | $4.5 \times 10^{8}$ (1) |
| New Haven    | $1.8 \times 10^{10}$ (13) | $2.0 \times 10^{8}$ (11) | $1.1 \times 10^{10}$ (59) | $5.1 \times 10^{8}$ (29) | $1.7 \times 10^{8}$ (1) |
| New London   | $2.1 \times 10^{10}$ (15) | $1.3 \times 10^{8}$ (6) | $1.3 \times 10^{10}$ (64) | $6.4 \times 10^{8}$ (30) | $0$ (0) |
| Tolland      | $1.1 \times 10^{10}$ (8)  | $8.1 \times 10^{8}$ (8) | $8.1 \times 10^{8}$ (76) | $1.6 \times 10^{8}$ (15) | $5.3 \times 10^{7}$ (1) |
| Windham      | $1.6 \times 10^{10}$ (11) | $1.4 \times 10^{8}$ (9) | $9.8 \times 10^{8}$ (60) | $5.0 \times 10^{8}$ (31) | $0$ (0) |
| Totals       | $1.4 \times 10^{11}$ (100)| $1.3 \times 10^{10}$ (9) | $9.1 \times 10^{10}$ (65) | $3.6 \times 10^{9}$ (23) | $6.2 \times 10^{8}$ (1) |

3. Results

Based on avoided SC–CO₂, the total estimated monetary mid-point value for TSC in the state of CT was $34.0B (i.e., 34.0 billion U.S. dollars, where B = billion = $10^{9}$), $23.7B for SOC (70% of the total value), and $10.3B for SIC (30% of the total value). Previously, we have reported that among the 48 conterminous states of the U.S., CT ranked 46th for TSC [30], 46th for SOC [31], and 40th for SIC [28].

3.1. Storage and Value of SOC by Soil Order and County for Connecticut

Soil orders with the highest midpoint monetary value for SOC were Inceptisols ($15.4B), Histosols ($6.0B), and Entisols ($2.2B) (Tables 5 and 6). The counties with the highest midpoint SOC values were Litchfield ($4.8B), New London ($3.5B), and New Haven ($3.0B) (Tables 5 and 6). Litchfield is the largest county with large areas of Inceptisols and Histosols (Table 3).

3.2. Storage and Value of SIC by Soil Order and County for Connecticut

Soil orders with the highest midpoint monetary value for SIC were Inceptisols ($8.8B), Entisols ($1.3B), and Histosols ($104.9M, where M = million = $10^{6}$) (Tables 7 and 8). The counties with the highest midpoint SIC values were Litchfield ($2.0B), Hartford ($1.6B), and New London ($1.4B) (Tables 7 and 8).

Table 6. Monetary value of soil organic carbon (SOC) by soil order and county for the state of Connecticut (USA), based on the areas shown in Table 3 and the area-normalized midpoint monetary values in Table 4.

| County       | Total SC-CO₂ ($) | Degree of Weathering and Soil Development |
|--------------|-----------------|------------------------------------------|
|              |                 | Slight (SC-CO₂ ($) = USD) | Moderate |
|              |                 | Entisols | Inceptisols | Histosols | Mollisols |
| Fairfield    | $2.9 \times 10^{9}$ | $2.8 \times 10^{8}$ | $2.0 \times 10^{8}$ | $6.6 \times 10^{8}$ | $4.7 \times 10^{8}$ |
| Hartford     | $3.0 \times 10^{9}$ | $7.0 \times 10^{8}$ | $1.9 \times 10^{8}$ | $3.3 \times 10^{8}$ | $3.1 \times 10^{8}$ |
| Litchfield   | $4.8 \times 10^{9}$ | $1.6 \times 10^{8}$ | $3.2 \times 10^{8}$ | $1.5 \times 10^{8}$ | $2.2 \times 10^{8}$ |
| Middlesex    | $1.9 \times 10^{9}$ | $1.2 \times 10^{8}$ | $1.2 \times 10^{8}$ | $5.2 \times 10^{7}$ | $7.7 \times 10^{6}$ |
| New Haven    | $3.0 \times 10^{9}$ | $3.4 \times 10^{8}$ | $1.8 \times 10^{8}$ | $8.6 \times 10^{7}$ | $2.9 \times 10^{7}$ |
| New London   | $3.5 \times 10^{9}$ | $2.1 \times 10^{8}$ | $2.3 \times 10^{8}$ | $1.1 \times 10^{8}$ | $0$ (0) |
| Tolland      | $1.8 \times 10^{9}$ | $1.4 \times 10^{8}$ | $1.4 \times 10^{8}$ | $2.7 \times 10^{8}$ | $9.0 \times 10^{6}$ |
| Windham      | $2.7 \times 10^{9}$ | $2.3 \times 10^{8}$ | $1.6 \times 10^{8}$ | $8.4 \times 10^{7}$ | $0$ (0) |
| Totals       | $2.4 \times 10^{10}$ | $2.2 \times 10^{9}$ | $1.5 \times 10^{10}$ | $6.0 \times 10^{9}$ | $1.0 \times 10^{8}$ |
Table 7. Midpoint soil inorganic carbon (SIC) storage by soil order and county for the state of Connecticut (USA), based on the areas shown in Table 3 and the midpoint SIC contents in Table 4.

| County      | Total SIC Storage (kg) (%) | Degree of Weathering and Soil Development | Slight | Moderate |
|-------------|---------------------------|-----------------------------------------|--------|----------|
|             |                           | Entisols | Inceptisols | Histosols | Mollisols |
|             |                           | Total SIC Storage (kg), (% of Total by County) |        |          |
| Fairfield   | $7.8 \times 10^6$ (13)    | $1.0 \times 10^7$ (13)                     | $6.7 \times 10^6$ (86)  | $6.7 \times 10^7$ (1) | $2.4 \times 10^8$ (0) |
| Hartford    | $9.3 \times 10^6$ (15)    | $2.5 \times 10^7$ (27)                     | $6.6 \times 10^6$ (71)  | $3.4 \times 10^7$ (0)  | $1.6 \times 10^8$ (2) |
| Litchfield  | $1.2 \times 10^7$ (19)    | $5.9 \times 10^7$ (5)                      | $1.1 \times 10^7$ (93)  | $1.5 \times 10^8$ (1)  | $1.1 \times 10^9$ (1) |
| Middlesex   | $4.7 \times 10^6$ (8)     | $4.3 \times 10^7$ (9)                      | $4.2 \times 10^6$ (89)  | $5.3 \times 10^7$ (1)  | $3.9 \times 10^8$ (1) |
| New Haven   | $7.5 \times 10^6$ (12)    | $1.2 \times 10^8$ (16)                     | $6.1 \times 10^7$ (81)  | $8.8 \times 10^7$ (1)  | $1.5 \times 10^8$ (2) |
| New London  | $8.5 \times 10^6$ (14)    | $7.6 \times 10^8$ (9)                      | $7.7 \times 10^8$ (90)  | $1.1 \times 10^9$ (1)  | 0 (0) |
| Tolland     | $5.2 \times 10^6$ (9)     | $4.9 \times 10^8$ (9)                      | $4.7 \times 10^8$ (89)  | $2.8 \times 10^9$ (1)  | $4.5 \times 10^9$ (1) |
| Windham     | $6.5 \times 10^6$ (11)    | $8.3 \times 10^8$ (13)                     | $5.6 \times 10^8$ (86)  | $8.5 \times 10^8$ (1)  | 0 (0) |
| Totals      | $6.1 \times 10^10$ (100) | $7.8 \times 10^9$ (13)                     | $5.2 \times 10^10$ (85) | $6.1 \times 10^9$ (1)  | $5.2 \times 10^9$ (1) |

Table 8. Monetary value of soil inorganic carbon (SIC) by soil order and county for the state of Connecticut (USA), based on the areas shown in Table 3 and the area-normalized midpoint monetary values in Table 4.

| County      | Total SC-CO₂ ($) | Degree of Weathering and Soil Development | Slight | Moderate |
|-------------|------------------|-----------------------------------------|--------|----------|
|             |                  | Entisols | Inceptisols | Histosols | Mollisols |
|             | Total SC-CO₂ ($) (USD) |        |          |          |          |
| Fairfield   | $1.3 \times 10^8$ | $1.7 \times 10^8$ | $1.1 \times 10^9$ | $1.2 \times 10^8$ | $4.0 \times 10^9$ |
| Hartford    | $1.6 \times 10^8$ | $4.3 \times 10^8$ | $1.1 \times 10^9$ | $5.8 \times 10^8$ | $2.6 \times 10^8$ |
| Litchfield  | $2.0 \times 10^8$ | $1.0 \times 10^9$ | $1.8 \times 10^8$ | $2.6 \times 10^8$ | $1.9 \times 10^8$ |
| Middlesex   | $7.9 \times 10^8$ | $7.3 \times 10^8$ | $7.1 \times 10^8$ | $9.1 \times 10^7$ | $6.5 \times 10^8$ |
| New Haven   | $1.3 \times 10^9$ | $2.1 \times 10^8$ | $1.0 \times 10^9$ | $1.5 \times 10^7$ | $2.5 \times 10^7$ |
| New London  | $1.4 \times 10^9$ | $1.3 \times 10^8$ | $1.3 \times 10^8$ | $1.9 \times 10^7$ | 0 (0) |
| Tolland     | $8.8 \times 10^8$ | $8.3 \times 10^7$ | $7.8 \times 10^8$ | $4.8 \times 10^6$ | $7.6 \times 10^6$ |
| Windham     | $1.1 \times 10^9$ | $1.4 \times 10^8$ | $9.5 \times 10^8$ | $1.5 \times 10^7$ | 0 (0) |
| Totals      | $1.0 \times 10^10$ | $1.3 \times 10^10$ | $8.8 \times 10^9$ | $1.0 \times 10^8$ | $8.8 \times 10^7$ |

3.3. Storage and Value of TSC (SOC + SIC) by Soil Order and County for Connecticut

Soil orders with the highest midpoint monetary value for TSC were Inceptisols ($24.2B), Histosols ($6.1B), and Entisols ($3.5B) (Tables 9 and 10). Inceptisols contributed 71% to the total social cost of TSC because of their large area in the state (84%). Despite the small area in CT (2% of the state area), Histosols ranked second with 18% of the total social cost of TSC because this soil type has high soil C content (142.5 kg m⁻²) and value ($24.03 m⁻²) (Table 4).

The counties with the highest midpoint TSC values were Litchfield ($6.8B), New London ($4.9B), and Hartford ($4.6B) (Tables 9 and 10). The soil order of Inceptisols is the largest contributor to TSC in all counties with contributions ranging from 66% to 81% (Table 9). In addition, the soil order of Inceptisols occupies the largest areas in all counties, which ranges from 70% to 92% of the total county area (Table 3).

It is important to note that the TSC content which has been described in terms of only soil orders and also as soil orders within administrative boundaries (counties) represent the potential soil carbon that could be released as a result of land conversions. This is equivalent to the largest potential carbon footprint from soil carbon. While it is unlikely that all soil carbon will be released from these carbon pools, large amounts of CO₂ can be lost through land conversions that occur during the development process.

The soil order of Histosols is especially sensitive to soil C loss. All CT’s counties have Histosols with Litchfield and New London possessing the highest monetary values of TSC (Table 10).
Table 9. Midpoint total soil carbon (TSC) storage by soil order and county for the state of Connecticut (USA), based on the areas shown in Table 3 and the midpoint TSC contents shown in Table 4.

| County   | Total TSC Storage (kg) (%) | Degree of Weathering and Soil Development | Total TSC Storage (kg, (% of Total by County)) |
|----------|----------------------------|------------------------------------------|-----------------------------------------------|
|          |                            | Slight Entisols | Inceptisols | Histosols | Molisols |
| Fairfield| $2.5 \times 10^{10}$ (12) | $2.7 \times 10^{10}$ (11) | $1.8 \times 10^{10}$ (73) | $4.0 \times 10^{10}$ (16) | $5.2 \times 10^{10}$ (0) |
| Hartford | $2.7 \times 10^{10}$ (13) | $6.7 \times 10^{10}$ (25) | $1.8 \times 10^{10}$ (67) | $2.0 \times 10^{10}$ (7) | $3.4 \times 10^{10}$ (1) |
| Litchfield| $4.0 \times 10^{10}$ (20)  | $1.6 \times 10^{10}$ (4)  | $3.0 \times 10^{10}$ (74) | $8.9 \times 10^{10}$ (22) | $2.5 \times 10^{10}$ (1) |
| Middlesex| $1.6 \times 10^{10}$ (8)   | $1.1 \times 10^{10}$ (7)  | $1.2 \times 10^{10}$ (72) | $3.2 \times 10^{10}$ (20) | $8.4 \times 10^{10}$ (1) |
| New Haven| $2.5 \times 10^{10}$ (13) | $3.2 \times 10^{10}$ (13) | $1.7 \times 10^{10}$ (66) | $5.2 \times 10^{10}$ (21) | $3.2 \times 10^{10}$ (1) |
| New London| $3.0 \times 10^{10}$ (15) | $2.0 \times 10^{10}$ (7)  | $2.1 \times 10^{10}$ (71) | $6.5 \times 10^{10}$ (22) | 0 (0) |
| Tolland  | $1.6 \times 10^{10}$ (8)   | $1.3 \times 10^{10}$ (8)  | $1.3 \times 10^{10}$ (81) | $1.7 \times 10^{10}$ (10) | $9.9 \times 10^{10}$ (1) |
| Windham  | $2.3 \times 10^{10}$ (11) | $2.2 \times 10^{10}$ (10) | $1.5 \times 10^{10}$ (68) | $5.1 \times 10^{10}$ (22) | 0 (0) |
| Totals   | $2.0 \times 10^{11}$ (100) | $2.1 \times 10^{10}$ (10) | $1.4 \times 10^{11}$ (71) | $3.6 \times 10^{10}$ (18) | $1.1 \times 10^{10}$ (1) |

Table 10. Monetary value of total soil carbon (TSC) by soil order and county for the state of Connecticut (USA), based on the areas shown in Table 3 and the area-normalized midpoint monetary values in Table 4.

| County   | Total SC-CO₂ ($) | Degree of Weathering and Soil Development | SC-CO₂ ($) = USD |
|----------|------------------|------------------------------------------|------------------|
|          |                  | Slight Entisols | Inceptisols | Histosols | Molisols |
| Fairfield| $4.2 \times 10^9$ | $4.6 \times 10^9$ | $3.1 \times 10^9$ | $6.7 \times 10^9$ | $8.7 \times 10^9$ |
| Hartford | $4.6 \times 10^9$ | $1.1 \times 10^9$ | $3.1 \times 10^9$ | $3.4 \times 10^9$ | $5.8 \times 10^9$ |
| Litchfield| $6.8 \times 10^9$ | $2.6 \times 10^9$ | $5.0 \times 10^9$ | $1.5 \times 10^9$ | $4.1 \times 10^9$ |
| Middlesex| $2.7 \times 10^9$ | $1.9 \times 10^9$ | $1.9 \times 10^9$ | $5.3 \times 10^9$ | $1.4 \times 10^9$ |
| New Haven| $4.3 \times 10^9$ | $5.4 \times 10^9$ | $2.8 \times 10^9$ | $8.8 \times 10^9$ | $5.4 \times 10^9$ |
| New London| $5.0 \times 10^9$ | $3.4 \times 10^9$ | $3.5 \times 10^9$ | $1.1 \times 10^9$ | 0 |
| Tolland  | $2.7 \times 10^9$ | $2.2 \times 10^9$ | $2.2 \times 10^9$ | $2.8 \times 10^9$ | $1.7 \times 10^9$ |
| Windham  | $3.8 \times 10^9$ | $3.8 \times 10^9$ | $2.6 \times 10^9$ | $8.5 \times 10^9$ | 0 |
| Totals   | $3.4 \times 10^{10}$ | $3.5 \times 10^{10}$ | $2.4 \times 10^{10}$ | $6.1 \times 10^{10}$ | $1.9 \times 10^{10}$ |

3.4. Land Use/Land Cover Change by Soil Order in Connecticut from 2001 to 2016

Connecticut experienced changes in land use/land cover (LULC) over the 15-year period (Table 11, Figure 3). Changes varied by soil order and original LULC classification, with most soil orders experiencing area losses in “low disturbance” LULC classes (e.g., evergreen forest, hay/pasture) while gaining in the areas of “developed” LULC classes. Overall, CT’s forest cover was reduced across all forest types between 2001 and 2016 (Table 11), which represents less overall carbon sequestration in forests. In an earlier study for CT, Tomasso and Leighton (2014) [21] reported that almost four percent of forests were converted to developments between 1985 and 2020, which likely implies forest loss predated our study. A separate study by Arnold et al. (2020) [22] found a loss of 466 km² of forest and a gain of 403 km² of development over a 30-year period 1985–2015. The development area represented 4.7 percent of CT, and they noted that development occurred both from forest and agricultural land cover conversion [22].

Our study found reductions in wetlands over the 15-year study period, with the largest loss occurring in the emergent herbaceous wetlands category (Table 11). These wetlands often contain soils rich in SOC (e.g., Histosols) and are commonly protected by state and federal regulations, so it is somewhat unexpected that there were sizable losses in this wetland category. For the time between 1985 and 2010, Tomasso and Leighton (2014) [21] found a relatively small reduction in forested wetlands (–0.19%). It is important to consider the land conversion of wetland areas because it can result in large potential GHG emissions because of the associated soil types with high C content (e.g., Histosols).
Table 11. Land use/land cover (LULC) change by soil order in Connecticut (USA) from 2001 to 2016.

| NLCD Land Cover Classes (LULC) | 2016 Total Area by LULC (km²) (Change in Area, 2001–2016, %) | Degree of Weathering and Soil Development | Moderate | Entisols | Inceptisols | Histosols | 2016 Area by Soil Order, km² (Change in Area, 2001–2016, %) |
|--------------------------------|-------------------------------------------------------------|------------------------------------------|---------|-----------|-------------|-----------|-------------------------------------------------|
| Barren land                    | 39.0 (−5.8%)                                               | Slight                                   |         | 19.1 (−6.3%) | 19.4 (−5.3%) | 0.5 (−12.5%) | 0.0 (100.0%)                                     |
| Woody wetlands                 | 1010.0 (0.4%)                                              | Slight                                   |         | 123.4 (0.6%) | 721.5 (−0.0%) | 164.4 (2.1%) | 0.8 (−2.3%)                                      |
| Shrub/Scrub                    | 50.0 (83.8%)                                               | Slight                                   |         | 5.7 (12.6%)  | 44.2 (100.3%) | 0.1 (45.3%)  | 0.1 (57.7%)                                      |
| Mixed forest                   | 1554.0 (−0.4%)                                             | Slight                                   |         | 124.0 (−0.9%) | 1415.4 (−0.3%) | 10.1 (−0.1%) | 4.5 (−1.1%)                                      |
| Deciduous forest               | 5569.7 (−2.7%)                                             | Slight                                   |         | 245.5 (−6.6%) | 5287.7 (−2.6%) | 15.1 (−2.2%) | 21.4 (−5.3%)                                     |
| Herbaceous                     | 102.6 (40.2%)                                              | Slight                                   |         | 20.7 (4.5%)  | 80.8 (53.3%)  | 0.6 (77.5%)  | 0.5 (51.9%)                                      |
| Evergreen forest               | 202.8 (−3.0%)                                              | Slight                                   |         | 34.8 (−5.5%)  | 165.7 (−2.5%) | 1.1 (−4.7%)  | 1.2 (−3.0%)                                      |
| Emergent herbaceous wetlands   | 76.7 (−4.6%)                                               | Slight                                   |         | 8.4 (−6.9%)   | 22.7 (−4.5%)  | 45.6 (−4.1%) | 0.0 (7.7%)                                       |
| Hay/Pasture                    | 476.7 (−7.0%)                                              | Slight                                   |         | 58.9 (−11.6%) | 413.6 (−6.4%) | 2.3 (−1.2%) | 1.9 (−10.2%)                                    |
| Cultivated crops               | 198.4 (3.2%)                                               | Slight                                   |         | 37.9 (−4.1%)  | 159.6 (5.0%)  | 0.2 (11.3%)  | 0.7 (15.8%)                                      |
| Developed, open space          | 1260.1 (3.1%)                                              | Moderate                                 |         | 208.1 (−1.1%) | 1035.8 (3.9%) | 8.6 (0.1%)  | 7.6 (5.6%)                                       |
| Developed, medium intensity    | 577.2 (11.1%)                                              | Moderate                                 |         | 311.6 (7.1%)  | 262.0 (16.0%) | 1.8 (28.0%) | 1.8 (24.6%)                                      |
| Developed, low intensity       | 898.4 (3.8%)                                               | Moderate                                 |         | 288.5 (−0.8%) | 599.8 (6.1%)  | 5.2 (3.7%)  | 4.9 (7.6%)                                       |
| Developed, high intensity      | 171.9 (18.5%)                                              | Moderate                                 |         | 139.6 (11.9%) | 31.9 (59.1%)  | 0.2 (32.0%) | 0.2 (101.5%)                                    |

Figure 3. Land cover map of Connecticut (U.S.A.) for 2016 (Latitude: 40°58' N to 42°03' N; Longitude: 71°47' W to 73°44' W) (based on data from [MRLC 27]).

4. Significance of Results

4.1. Significance of Results for Connecticut’s GHG Emissions Inventory and Global Warming Solutions Act

Although the state of CT is committed to reducing GHG emissions by 80 percent below 2001 levels by 2050 [16], it is currently not on track to meet these goals according to the CT’s GHG emissions inventory [32]. Furthermore, the CT’s GHG emissions inventory is incomplete because it does not consider soil C storage and soil-based emissions from land conversions. This study provides quantitative information about CT’s soil portfolio and its C regulating ES, which shows the soil’s potential for GHG emissions (Table 12). Most of the CT’s soils are slightly weathered soils with low recarbonization potential (Table 12).
Table 12. Distribution of soil carbon regulating ecosystem services in the state of Connecticut (USA) by soil order (photos courtesy of USDA/NRCS [33]). Values are taken/derived from Tables 3, 6 and 8 and Table 10.

| Degree of Weathering and Soil Development | Entisols | Inceptisols | Histosols | Mollisols |
|------------------------------------------|---------|------------|-----------|----------|
| Slight 99% | 13%     | 84%        | 2%        | 1%       |
| Moderate 1% |         |            |           |          |

Social cost of soil organic carbon (SOC): $23.7B

| Degree of Weathering and Soil Development | Entisols | Inceptisols | Histosols | Mollisols |
|------------------------------------------|---------|------------|-----------|----------|
| Slight 99% | 13%     | 84%        | 2%        | 1%       |
| Moderate 1% |         |            |           |          |

Social cost of soil inorganic carbon (SIC): $10.3B

| Degree of Weathering and Soil Development | Entisols | Inceptisols | Histosols | Mollisols |
|------------------------------------------|---------|------------|-----------|----------|
| Slight 99% | 13%     | 84%        | 2%        | 1%       |
| Moderate 1% |         |            |           |          |

Social cost of total soil carbon (TSC): $34.0B

| Degree of Weathering and Soil Development | Entisols | Inceptisols | Histosols | Mollisols |
|------------------------------------------|---------|------------|-----------|----------|
| Slight 99% | 13%     | 84%        | 2%        | 1%       |
| Moderate 1% |         |            |           |          |

Sensitivity to climate change

| Degree of Weathering and Soil Development | Entisols | Inceptisols | Histosols | Mollisols |
|------------------------------------------|---------|------------|-----------|----------|
| Slight 99% | 13%     | 84%        | 2%        | 1%       |
| Moderate 1% |         |            |           |          |

SOC and SIC sequestration (recarbonization) potential

| Degree of Weathering and Soil Development | Entisols | Inceptisols | Histosols | Mollisols |
|------------------------------------------|---------|------------|-----------|----------|
| Slight 99% | 13%     | 84%        | 2%        | 1%       |
| Moderate 1% |         |            |           |          |

Areas with the soil order of Histosols are the “hotspot” with high soil C content and high sensitivity to climate change and disturbance (Table 12).

Our study showed that soil-based emissions from land conversions in CT between 2001 and 2016 resulted in a total CF value of $383.3M, with 37% of the value associated with medium intensity developments ($140.8M) (Table 13). The soil order of Inceptisols generated the highest social costs of C in most of the development classes except for high-intensity developments (Table 13). The soil order of Inceptisols occupies the largest area in CT (84% of the total state area) (Table 12). The soil order of Histosols shows increases in development even though Histosols are often associated with wetlands, which are commonly protected at the state and federal levels (Table 14).

The state of CT currently reports its consumption-based emission estimates for each economic sector (e.g., residential, transportation, electric consumption, commercial, industrial, agriculture, and municipal waste) [32]. Emissions from land conversions in CT are also driven by consumption and should be included in the GHG emission inventory. Remote sensing techniques can be used to monitor land-use changes on an ongoing basis to determine GHG emissions estimates associated with land conversions.
Table 13. Increases in developed land and maximum potential for realized social costs of carbon due to complete loss of total soil carbon (TSC) of developed land by soil order in Connecticut (USA) from 2001 to 2016. Values are derived from Tables 4 and 11.

| NLCD Land Cover Classes (LULC) | Degree of Weathering and Soil Development | Area Change, km² (SC-CO₂, $ = USD) |
|-------------------------------|------------------------------------------|------------------------------------|
| Developed, open space (39.6 km², $94.2M) | Slight: Entisols 39.2 ($92.5M) | Moderate: Mollisols 0.4 ($1.7M) |
| Developed, medium intensity (57.6 km², $140.8M) | Entisols 20.7 ($44.9M) | Inceptisols 36.1 ($85.1M) | Histosols 0.4 ($9.3M) | Mollisols 0.3 ($1.5M) |
| Developed, low intensity (35.1 km², $87.5M) | Entisols 14.9 ($32.3M) | Inceptisols 11.8 ($27.9M) | Moderate: Mollisols 0.1 ($5,115,000.0) |
| Developed, high intensity (26.8 km², $60.7M) | Slight: Entisols - 39.2 ($92.5M) | Moderate: Mollisols - 0.4 ($1.7M) |
| Totals (159.1 km², $383.3M) | 35.6 ($77.2M) | 121.7 ($287.1M) | 0.6 ($13.7M) | 1.2 ($5.1M) |

Note: Entisols, Inceptisols, and Mollisols are mineral soils. Histosols are mostly organic soils. M = million = 10⁶.

Table 14. Increases in land development (LULC: developed open space, developed medium intensity, developed low intensity, and developed high intensity) and maximum potential for realized social costs of C due to complete loss of total soil carbon (TSC) of developed land by soil order and county in Connecticut (USA) from 2001 to 2016.

| County | Total Area Change (km²) (SC-CO₂, $ = USD) | Degree of Weathering and Soil Development | Developed Area Increase between 2001 and 2016 (km²) (SC-CO₂, $ = USD) |
|--------|------------------------------------------|------------------------------------------|--------------------------------------------------|
| Fairfield | 31.6 ($75.6M) | Slight: Entisols 5.7 ($12.3M) | Developed Area Increase | Moderate: Mollisols 0 |
| Hartford | 49.5 ($117.3M) | Entisols 15.2 ($33.0M) | Inceptisols 33.4 ($78.9M) | Histosols 0.1 ($2.4M) | Mollisols 0.7 ($3.1M) |
| Litchfield | 7.0 ($16.3M) | Entisols 1.3 ($2.7M) | Inceptisols 5.8 ($13.6M) | Moderate: Mollisols 0 |
| Middlesex | 11.5 ($28.9M) | Entisols 1.8 ($3.8M) | Inceptisols 9.6 ($22.7M) | Histosols 0.1 ($2.4M) | Moderate: Mollisols 0 |
| New Haven | 32.6 ($80.4M) | Entisols 7.4 ($16.0M) | Inceptisols 24.9 ($58.7M) | Histosols 0.2 ($4.8M) | Mollisols 0.2 ($842,000.0) |
| New London | 14.0 ($32.4M) | Entisols 3.1 ($6.8M) | Inceptisols 10.9 ($25.6M) | Moderate: Mollisols 0 |
| Tolland | 8.7 ($20.6M) | Entisols 1.4 ($2.9M) | Inceptisols 7.2 ($16.9M) | Moderate: Mollisols 0.2 ($697,630.8) |
| Windham | 7.3 ($16.6M) | Entisols 3.2 ($6.8M) | Inceptisols 4.1 ($9.8M) | Moderate: Mollisols 0 |
| Totals | 162.2 ($388.1M) | Developed Area Increase | Moderate: Mollisols 0.5 ($12.0M) | 1.1 ($4.6M) |

Spatial analysis revealed that most of the social costs of C emissions from land conversions were associated with Hartford ($117.3M), New Haven ($80.4M), and Fairfield counties ($75.6M) (Table 14, Figure 4). Figure 4 demonstrates the spatial pattern of CT’s CF from land conversions between 2001 and 2016. These results can be made more detailed and identify individual contributions to CF if needed. It should be noted that this CF is one example of many CF’s from land conversions in the history of CT. This type of analysis can be conducted to determine the historic contributions of land conversions to CF in CT, the country as a whole, and “ecological debt” [20].

Results of this study partially fill a research gap in connecting land conversions to the social costs of C emissions. Results of this study support findings by Arnold et al. (2020) [22], which also documented an increase in developments (sprawl, away from existing developments) in CT at the expense of agriculturally productive soils (flat and well-drained) and forests. Sprawl-type development in CT further aggravates the GHG emissions from other sources (e.g., transportation, etc.). According to Feng and Gauthier (2021) [34], urban sprawl type development makes remarkable contributions to climate change, which should be measured. Our study contributes quantitative and monetary analysis of contributions of land conversions to CF of developments, which can be used in land-use and climate change planning in CT.
Figure 4. The total dollar value of mid-point total soil carbon (TSC) storage value for newly “developed” land covers (open space, low, medium, and high intensity) from 2001 to 2016 in Connecticut (U.S.A.) based on a social cost of C (SC-CO$_2$) of $46 per metric ton of CO$_2$ applicable for the year 2025 (2007 U.S. dollars with an average discount rate of 3% [10]).

4.2. Significance of Results in Broader Context

Transportation and land-use change are identified as some of the primary anthropogenic sources of atmospheric CO$_2$ increases, which contribute to climate change [35]. Climate change has adverse impacts on CT including the effect of sea-level rise on the state (Figure 5) [15]. Emissions from land cover conversions are often omitted from GHG inventories and CF, which creates a problem of incomplete accounting of GHG emissions. Omission of land conversion CF is often associated with a lack of integration of soil and land resources [22].

Figure 5. Projections of future sea rise due to climate change in Connecticut.
This study makes a unique scientific contribution to the understanding of soil-based CF from land conversions and in developing a method, which integrates soil and land resources to identify CF associated with land conversions using the state of CT as a case study. The results of this study provide the following insights on soil-based CF from land conversions [33]:

- **Definition of CF**: Soil CF is defined as GHG emissions because of land disturbances from various soil types and events expressed as carbon dioxide (CO$_2$) equivalent, which can be expressed in monetary terms (e.g., social costs of C, etc.).
- **Drivers**: Soil CF is commonly caused by natural and/or anthropogenic (e.g., urban development) disturbances. Anthropogenic drivers often include land consumption-based new developments (e.g., new home construction).
- **Elements**: Soil CF has spatial (e.g., science-based, administrative, etc.) and temporal (e.g., event) scales, and can have different intensities (e.g., low, medium, and high-intensity developments). Soil CF has the composition (e.g., soil type, land cover, soil C content, etc.).
- **Measurements**: Soil CF is determined by using the area of land disturbance and soil C content to calculate the maximum potential for realized social costs of C (SC-CO$_2$) from each disturbance based on land cover change analysis (Figure 1). These estimates can be performed at various administrative and spatial scales (Figure 1).
- **Dynamics**: Soil CF results in soil and land cover transformations leading to biophysical and socio-economic transformations. The consequences of these transformations extend beyond the boundaries of CF since GHG emissions extend outside the boundaries of the CF.
- **Effects**: Soil CF results not only in GHG emissions, but in biodiversity loss, increase in impervious surface, and reduction in both agricultural and forest lands and the future sequestration potential of these lands.
- **Consequences**: Soil CF reduces the overall ecosystem goods and services provided by the land while creating soil erosion [36], urban heat islands [37], and increasing ground surface temperatures which can reduce carbon sequestration potential. Changes can also reduce ecosystem resilience.
- **Outcomes**: Soil CF contributes directly to climate change while also increasing the vulnerabilities of ecosystems to climate change.

In conclusion, our study improved the understanding of the application of soil CF from land conversions for the state of CT and beyond. These land conversions had both direct and indirect impacts on climate change. When these land conversions are associated with urban sprawl, which indicates a lower density of housing units, there are likely CF impacts beyond the soil CF because of the increased human transportation costs and increased rate of destruction of land covers that have future sequestration potential [34].

This study could also provide insights into reducing future CF from land conversions by considering the soil types in CT. Soil types have various optimal uses based on their C contents and environmental characteristics (Table 12). For the state of CT, Mollisols (1% of state area) are agriculturally important soils because of high C content and should likely be reserved for agriculture. Histosols in CT (2% of state area) also have high soil C content and can be legally restricted from development to preserve wetland areas. Entisols are often found in floodplains or steep slope areas which are not recommended for development. Increased flood risk associated with climate change threatens any development in these floodplain areas. Inceptisols are the most common soils in CT (84% of state area), where most land conversions have occurred from 2001 to 2016. New developments in the state of CT are sprawl-type developments, which are characterized by outward low-density commercial and residential developments away from densely urbanized areas [34]. Based on the CT’s soil diversity, land conversions should be limited to Inceptisols which have lower soil C content. Avoiding future sprawl-type developments would further reduce CT’s future CF.
Climate-change linked sea-level rise will likely displace people from various coastal cities in the United States [38] and CT (Figure 5). Considering the large proportion of private land ownership in CT (93.8%), the private land market will need to respond to this relocation demand for people who stay within the state of CT. It may be necessary to consider the soil diversity, existing land covers, and land ownership to minimize the CF impact of these expected population displacements. Sea-level rise, and other climate change impacts, are expected to be worldwide [39], and the methods presented contribute to the study of how to help measure the CF and minimize the CF in the future.

5. Conclusions

Carbon footprint is increasingly being used to analyze GHG emissions at the state level, but the term “carbon footprint” can have different interpretations depending on the type and source of emissions. The carbon footprint of soil-based emissions from land conversions is often being excluded from the state’s GHG inventories, which can lead to an underestimate of the state’s total CF. This study examined the application of the concept of CF to soil-based emissions from land conversions in CT. This study followed a conventional three-step process for CF estimation, which involves the selection of GHG, boundary setting, and GHG emission data gathering. Soil-based CO₂ emissions from land conversions were identified as a GHG and analyzed by soil order, land cover, state, and county using soil data and remote sensing analysis between 2001 and 2016. This study revealed unique aspects of CF as applied to soil-based emissions from land conversions. The term CF implies a measure of area, which is well suited for spatial analysis of soil and land cover for any location. It should be noted the number and types of soils, and land covers in the area of consideration represent the maximum potential C storage that can be released upon disturbance. Only a portion of this potential C storage will be released in any time period as GHG emissions, which would constitute the soil-based CF. With that in mind, this study first determined the number and aerial extent of soil types, soil C storage, and land covers in CT.

Pedodiversity of CT defines the soil C content and the value of regulating ES/ED from soil organic carbon (SOC), soil inorganic carbon (SIC), and total soil carbon (TSC) stocks, which can be valued based on the concept of the avoided social cost of carbon dioxide (CO₂) emissions. The total estimated monetary mid-point value for TSC stocks in the state of Connecticut was $34.0B (i.e., 34.0 billion U.S. dollars, where B = billion = 10⁹), $23.7B for SOC (70% of the total value), and $10.3B for SIC (30% of the total value). Soil orders with the highest midpoint monetary value for SOC were Inceptisols ($15.4B), Histosols ($6.0B), and Entisols ($2.2B). Soil orders with the highest midpoint monetary value for SIC were Inceptisols ($8.8B), Entisols ($1.3B), and Histosols ($104.9M, where M = million = 10⁶). Soil orders with the highest midpoint monetary value for TSC were Inceptisols ($24.2B), Histosols ($6.1B), and Entisols ($3.5B). The counties with the highest midpoint SOC values were Litchfield ($4.8B), New London ($3.5B), and New Haven ($3.0B). The counties with the highest midpoint SIC values were Litchfield ($2.0B), Hartford ($1.6B), and New London ($1.4B). The counties with the highest midpoint TSC values were Litchfield ($6.8B), New London ($4.9B), and Hartford ($4.6B).

The actual CF was determined by identifying individual areas or pixels where land cover changed between low-intensity and high-intensity land uses, which indicated areas of disturbance with CO₂ emissions in CT between 2001 and 2016. These multiple CFs were summarized by soil type, county, and land cover class. Connecticut has experienced land use/land cover (LULC) changes, which resulted in $388.1M worth of “realized” social costs of carbon dioxide emissions, primarily associated with the soil order of Inceptisols ($287.1M). The counties that have exhibited the most developments were Hartford ($117.3M), New Haven ($80.4M), and Fairfield ($75.6M) counties. The same techniques could be used to determine the CF of any spatial extent or division within the state of CT (e.g., housing development, parcel, etc.). Carbon footprint is often used to represent current GHG emissions, but the techniques presented in this study could be used to model different
development scenarios to estimate potential CFs to guide climate change policies that help limit GHG emissions. This study demonstrates that there may be a missing step in conventional CF determination when applied to soil-based emissions from land conversions because it is necessary to first evaluate the potential GHG source characteristics (e.g., types of soil orders, their location, and extent, C storage, etc.). This information helps determine the patterns of past and current CFs, as well as helps develop policies and regulations to minimize CFs in the future.

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Glossary

| Acronym | Definition                      |
|---------|--------------------------------|
| CF      | Carbon footprint               |
| ED      | Ecosystem disservices          |
| ES      | Ecosystem services             |
| EPA     | Environmental Protection Agency|
| SC-CO2  | 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|
| STATSGO | State Soil Geographic Database |
| TSC     | Total soil carbon              |
| USDA    | United States Department of Agriculture |

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