Comparing soil carbon estimates in glaciated soils at a farm scale using geospatial analysis of field and SSURGO data

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ABSTRACT

Soil carbon is a key soil property related to ecosystem services and it is often used in soil carbon content estimates at various scales. Uncertainties in soil carbon estimates often arise from variability in field, laboratory, and/or geospatial data at a farm scale. The objectives of this study were to quantify and compare levels of soil organic carbon (SOC), soil inorganic carbon (SIC), and total soil carbon (TC) for a 147-hectare field site in upstate New York based on three alternative analysis procedures: a) using carbon concentrations reported by the Soil Survey Geographic (SSURGO) spatial databases for each soil map unit (SMU) present at the field site and applying that value across each SMU; b) averaging the carbon contents of soil cores collected within a specific SMU boundary and applying the averaged value across each SMU; and c) interpolating carbon contents across the field site based on the individual soil cores. Maps of SOC, SIC, and TC contents based on the interpolated core samples were different from maps created by applying averaged core results or SSURGO values across the SMUs. Differences in the magnitudes and spatial distributions of carbon can be attributed to several factors. For example, SSURGO soil carbon values are frequently measured for a selected pedon(s) from a “type location” and not from the actual study location. These “type locations” can be located far from study sites and even in different states. Also, SSURGO soil carbon values may overestimate the actual contents when compared to systematic field measurements because the SSURGO values at lower depths are often extrapolated from upper soil horizons. Such extrapolations affect inorganic carbon to a much greater extent than organic carbon, therefore better agreement is observed in the present study between SOC estimates from the SSURGO database and field measurements. Because regional

and/or global carbon estimates are rarely made with detailed field data due to the high costs of field and laboratory measurements, additional field sampling is needed to constrain and improve these estimates and also to assess the potential variability present.

Keywords: ecosystem services, functions, GIS, mapping, pedons, pool, soil inorganic carbon (SIC), soil organic carbon (SOC), stock, storage, total carbon (TC)

1. Introduction

Terrestrial soil carbon stocks and cycling are poorly understood because of a lack of detailed field data on soil organic carbon (SOC), soil inorganic carbon (SIC), and total soil carbon (TC) for specific areas and the world in general (Dawson and Smith, 2007). Even when data are available, there is uncertainty in estimates from variability in measurements and analyses (Dawson and Smith, 2007; Schwager and Mikhailova, 2002). Soil organic carbon has been identified as a key soil property linked to ecosystem services such as provisional services (e.g., food, fuel, fiber), regulating services (e.g., climate and greenhouse gas regulation), cultural services (e.g., recreation, ecotourism), and supporting services (e.g., weathering, soil formation, nutrient cycling) (Adhikari and Hartemink, 2016).

The most common technique for estimating carbon stocks is the “measure-and-multiply” approach, which has been used for national (Cambule et al., 2014; Kern, 1994; Guo et al., 2006), regional (Tan et al., 2009; Thompson and Kolka, 2005) and global carbon estimates (Batjes et al., 2007). In the U.S., midpoint soil carbon values from the State Soil Geographic (STATSGO) and the Soil Survey Geographic (SSURGO)

databases have been used to estimate soil carbon contents at a variety of spatial scales. The STATSGO database (map scale of 1:250,000) is generalized from the more detailed SSURGO (map scale of 1:12,000) database and both share soil pedon information. Several studies have compared soil carbon estimated using STATSGO and SSURGO with the common conclusion that estimates of soil carbon vary from these databases (Davidson and Lefebvre, 1993; Wu et al., 2001; Rasmussen, 2006). In contrast, few studies have compared SSURGO soil carbon estimates against actual field measurements (Zhong and Xu, 2011). For example, Zhong and Xu (2011) compared SOC estimates in Louisiana using STATSGO, SSURGO and field measurements and concluded that SSURGO and field SOC estimates showed a closer match.

The SSURGO database contains soil information collected by the National Cooperative Soil Survey based on field and laboratory analyses (Soil Survey Staff, 2015). The information is displayed by soil map unit (SMU) and is available for most areas in the U.S. and the Territories, Commonwealths and Island Nations served by the USDA-NRCS (Soil Survey Staff, 2015). The map units describe soils with unique properties, interpretations, and productivity (Soil Survey Staff, 2015). Each map unit may contain one to three major components and some minor components (Soil Survey Staff, 2015). The map units are typically named for the major components (Soil Survey Staff, 2015). Soil information is reported for scales ranging from 1:12,000 (more detailed) to 1:63,360 (Soil Survey Staff, 2015).

Previous research efforts have focused primarily on estimating SOC from STATSGO and SSURGO databases, but only rarely making comparisons against actual field measurements within the soil map units. This study was aimed at conducting a more

comprehensive assessment – not only of SOC but also SIC and TC – and comparing the “measure-and-multiply” approach using SSURGO and field measurements at a farm scale. The specific objectives of the study were to: 1) quantify contents and storage of soil organic carbon (SOC), soil inorganic carbon (SIC), and total soil carbon (TC) from averaged and interpolated soil core measurements using SSURGO soils boundaries, 2) compare these field carbon estimates with estimates of SOC, SIC and TC based on existing SSURGO database information, and 3) discuss implications for relying on SSURGO database estimates for soil carbon at a farm scale, particularly for the types of glaciated soils existing at the present study site.

2. Materials and methods

2.1. Study area

The Cornell University Willsboro Research Farm (44° 22' N, 73° 26' W; Fig. 1) is located near Willsboro in Essex County in northeastern New York State (Sogbedji et al., 2000). The research farm has an area of approximately 150 ha and is situated on the gently rolling lacustrine plain adjacent to Lake Champlain (Mikhailova et al., 1996). The climate in the area is temperate with a 150-day growing season (Mikhailova et al., 1996). Soils (Table 1) are highly variable as a result of glacial deposits (e.g., glacial till, deltaic or glacial like sands and clays) and include the soil orders Entisols, Inceptisols and Alfisols (Mikhailova et al., 1996).

2.2. Sampling

Fifty-four soil cores were collected on the Willsboro research farm in the summer of 1995 based on a regular square grid sampling pattern (Fig. 1), with each grid being 137.16 meters by 137.16 meters. Coordinates (NAD27 State Plane Coordinate System's New York East Zone, using Station ESSEX2 and Poke-A-Moonshine L.O.T. and Bench Mark H 395) and elevation values for the sample locations were obtained from a professional land survey team that used an Intelligent Total Station, Set 2C SOKKISHA (Standard deviation: ± 3 mm + 2 ppmD) (Mikhailova et al., 1996). Undisturbed soil cores of variable depth (sample depth varied due to the actual possibility of obtaining the sample) were extracted using a Giddings hydraulic sampler (Model – GSR-T-S) and plastic tubes with the average diameter of 4.5 cm (Mikhailova et al., 1996).

2.3. Laboratory analysis

Plastic tubes with soil samples closed with plastic caps were stored vertically in a refrigerator at approximately 1°C until processing and analysis (Mikhailova et al., 1996). Each soil core was sectioned into depth intervals and measurements were made of the coarse fraction (percent of soil sample greater than 2 mm) and reaction to weak HCl (“0” = no reaction, “1” = presence of effervescence). After removing the measured coarse fraction content, the sectioned soil samples were air-dried, manually ground and passed through a 2-mm mesh sieve. Total soil carbon (TC) content was determined by dry-combustion spectrometry using a Robo-prep-Tracemass system (Europa Scientific, Cheshire, UK). Samples that reacted to weak HCl were treated to remove carbonates and analyzed again for carbon, thus providing a direct measurement of SOC content. The difference in carbon content before and after treatment to remove carbonates was used to

determine SIC. A more in-depth discussion of the laboratory procedures and measurements have been reported by Mikhailova et al. (1996).

2.4. Determining SOC, SIC and TC Contents of Soil Cores

The organic carbon content (kg-OC/m²) associated with each soil core (to the depth sampled) was determined with the following equation:

$$C_{SOC} = \sum \{OC\% * \rho_b * Th * (1 - \delta_{2mm}/100) / 10\} \quad (1)$$

where C_{SOC} is the total organic carbon content (kg-OC/m²) associated with the soil core, OC% is the measured percent organic carbon (g-OC per 100 g soil) of a specific layer from the soil core (≤ 2 -mm particle size fraction), ρ_b is the bulk density (g/cm³) of the soil layer, Th is the thickness (cm) of the soil layer, and δ_{2mm} is the percent of coarse fragments in the soil layer that were larger than 2 mm in diameter (g-coarse fragments per 100 g soil). In the equation above, the term in parentheses accounts for the coarse fraction of the soil layer which had been removed prior to laboratory analysis while division by 10 converts to the proper units for SOC content. The organic carbon content of each soil layer in the core was then summed to obtain C_{SOC} for the entire soil core. All parameters on the right hand side of the equation were measured for the soil cores collected from the field, except for the bulk density which was taken as the midpoint value from the SSURGO data base for each soil layer. Calculations analogous to the one shown above were used to determine the SIC content (C_{SIC} , kg-IC/m²) and TC content (C_{TC} , kg-C/m²) of each soil core by using the IC% and TC%, respectively, of each soil layer in lieu of the OC%.

2.5. Spatial analysis: Determining SOC, SIC and TC contents and storage for SMUs based on reported SSURGO data and averaged soil core results

Using available information from the SSURGO database (e.g., midpoint values with depth of OC%, IC%, TC% and ρ_B values for each SMU) together with midpoint values of the coarse fraction with depth from the official NRCS soil series descriptions, SOC, SIC and TC contents were summed to the depth reported for each SMU equivalently to Equation 1 above (SSURGO estimates, Table 3). The average content value for each SMU was then multiplied by its corresponding area within ArcGIS 10.3 (ESRI, 2015) to determine total storage values for each SMU. From the field measurements, SOC, SIC and TC contents of soil cores taken from a specific SMU were averaged to obtain mean values that could be applied evenly across the SMU (averaged field estimates, Table 4). In a similar fashion, SOC, SIC and TC storage values based on these averaged soil core results were calculated by multiplying the SMU-averaged content values by the specific SMU area.

2.6. Spatial analysis: Interpolation of SOC, SIC and TC contents from field measurements and summing by SSURGO boundaries to determine SMU storage values

Inverse distance squared weighting from the twelve nearest sampling points was used to interpolate results from the 54 soil cores across the extent of the study area using a 1-m grid cell size in ArcGIS 10.3 (ESRI, 2015). This process created maps that estimated SOC, SIC and TC contents for each square meter of the field site. The interpolated content values (kg/m^2) were then multiplied by the 1-m^2 area of each grid cell before summing by SSURGO soil boundary to obtain total carbon storage values

(kg) for each SMU (interpolated field estimates, Table 5). With each interpolated content map, the summation function of zonal statistics in ArcGIS 10.3 was used to compute total SOC, SIC and TC storage associated with each SSURGO polygon/SMU.

3. Results and discussion

3.1. Estimating contents of soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC) for the soils present at the Willsboro Research Farm

Field data collected from the Willsboro Farm revealed that soil core depth and mean total soil SOC, SIC and TC inventories were highly variable (Table 4). This can be attributed to the fact that these soils are formed in glacial landscapes (e.g., till plains, lake plains, terraces, deltas, and outwash plains). Table 4 also shows that with a regular grid sampling approach, soil cores may not always be collected from each SMU present at a field site – this is particularly true with the smaller SMUs that may be present. One tactic to resolve this potential shortcoming in sampling is to utilize interpolation of the soil core results such that complete coverage is obtained (Table 5).

Upon comparing the three different approaches investigated in this study, one sees that the SSURGO midpoint values (Table 3) tended to be higher for SOC, SIC and TC contents versus the two approaches utilizing field measurements. For example, among the soils having measurable levels of inorganic carbon, averaged soil core results for SIC contents of the SMUs ranged from 75% lower (CuA) to 98% lower (CqB) than their respective SSURGO values. For TC contents, the averaged soil core values ranged from 41% lower (StA) to 76% lower (NeC) than the respective SSURGO values. Only the Deerfield sandy loam soil (DeA), which contained no inorganic carbon, deviated from

this overall trend in SIC and TC contents. In contrast, values for the SOC contents of SMUs showed less deviation: averaged soil core results for SOC contents of the SMUs ranged from 42% lower (StA) to 16% higher (KyA) than their corresponding SSURGO values.

Parallel trends in SOC, SIC and TC contents were observed with the interpolated soil core results versus corresponding SSURGO values, although there were slight differences in the values themselves and the ranges were slightly broader, in general. For example, interpolated soil core results for SOC contents of the SMUs ranged from 57% lower (CvA) to 31% higher (HgB) than their corresponding SSURGO values. Interpolated soil core results for SIC contents of the SMUs ranged from 71% lower (CvA) to 95% lower (KyB, CqB and McB) than their respective SSURGO values, while for TC contents the interpolated soil core values ranged from 35% lower (StA) to 79% lower (McB) than the respective SSURGO values.

By examining soil carbon contents at the Willsboro Research Farm based on soil order rather than SMU, one can analyze the alternative estimation approaches at a larger scale. For example, comparing values in Tables 3, 4 and 5 reveals very good agreement among the alternative estimates for the SOC content of total Alfisols on the farm. For the other two soil orders, however, the two field-based SOC estimates were lower than the corresponding SSURGO SOC values (i.e., ~ 20% lower and ~ 30% lower for total Inceptisols and Entisols, respectively). Consistent with the findings at the smaller SMU-scale, the field-based estimates for SIC and TC contents for the three soil orders were much lower than the corresponding values estimated from the SSURGO database. For example, for total Alfisols the field estimates for SIC and TC contents were ~ 90% lower

and ~ 65% lower, respectively, than SSURGO values. Similarly, field estimates for SIC and TC contents were lower by ~ 85% and ~50%, respectively, for total Entisols and were lower by ~ 90% and 70%, respectively, for total Inceptisols.

The higher values typically obtained with the SSURGO estimation approach likely results from the greater reported soil depth used in the database, which is consistent with the larger discrepancy generally observed for inorganic carbon versus organic carbon. However, because SSURGO data are based on field and laboratory results from “type location” per SMU (which can be located outside of state boundaries), they often lack measures of variability associated with actual soil depth and soil properties, including carbon. Also, because values in SSURGO often are extrapolated with depth (Guo et al., 2006), measured field values provide more accurate information, particularly for SIC. These shortcomings of the SSURGO database are particularly evident, therefore, when soils are highly variable at a farm scale (e.g., glaciated soils as with the present study).

3.2. Spatial comparison of SOC content at the Willsboro Research Farm

Although the SSURGO-based (Fig. 2a) and averaged soil core-based (Fig. 2b) estimation approaches yielded somewhat similar looking maps for the distribution of SOC concentrations across the SMUs at the Willsboro farm, there were several noticeable differences. In general, the SSURGO approach led to higher SOC estimates for some SMUs and slightly lower values for others. For the averaged soil core map presented in Fig. 2b, it is important to note that four SMUs were not sampled and therefore show up in the map as having content values of 0 kg/m². Interpolation of the

soil core values eliminates this anomaly (Fig. 2c) and shows a more varied estimate of SOC content over the study area, but does not greatly affect SOC concentrations for the SMUs relative to the SSURGO values as evident in the tabulated results.

3.3. Spatial comparison of SIC content at the Willsboro Research Farm

As noted above, greater differences were obtained between the SSURGO estimates for SIC concentrations across the farm and the corresponding field measurements. In nearly all cases, the SIC field core sample results averaged by SMU (Fig. 3b) as well as the interpolated soil core sample results (Fig. 3c) were much lower compared to reported SSURGO database SIC estimates (Fig. 3a) because of the high reported SIC values at the lower soil depths in the SSURGO database. Once again, the missing sample values for four SMUs appear in Fig. 3b as values of 0 kg/m². SSURGO SIC values are frequently measured from a selected pedon from a “type location” and not from the actual study location. These “type locations” can be located far from study sites and even in different states. SSURGO SIC values may overestimate the actual content when compared to systematic field measurements. The interpolated soil map of inorganic carbon suggests that its distribution is highly variable across the farm.

3.4. Spatial comparison of TC content at the Willsboro Research Farm

In general, the distribution of TC at the Willsboro Farm falls between the results described above for its SOC and SIC contributions. As with SOC concentrations, Figs. 4a and 4b show some similarities in their presentation of results although the overall magnitudes of the SSURGO TC estimates are much higher due to the influence of

inorganic carbon. Once again, interpolating the field measurements (Fig. 4c) removes the anomalous 0 kg/m² values for the four missing SMUs in Fig. 4b.

3.5. Analyzing the alternative approaches to estimate carbon contents and storage at the Willsboro Research Farm

To present a clearer comparison of the three approaches used to create the maps in Figures 2, 3 and 4, correlation plots were made to further examine the carbon estimates for each SMU (Fig. 5). As can be seen, much scatter exists in the estimates by SMU, including the estimates obtained with the two field measurement-based approaches. For SOC contents of the different SMUs, only the correlation between SSURGO estimates and averaged soil core estimates proved to be statistically significant ($r = 0.729$, $p = 0.017$). In contrast, the correlation between SSURGO SOC estimates and interpolated soil core SOC estimates for the SMUs was weakly negative ($r = -0.135$) but not statistically significant ($p = 0.645$). Likewise, the weak positive correlation ($r = 0.301$) observed between the field-averaged and field-interpolated SOC estimates for the SMUs was not statistically significant ($p = 0.398$). For the SIC estimates, the only significant correlation was found between SSURGO and interpolated soil core results ($r = 0.593$, $p = 0.025$); correlations of $r = 0.469$ ($p = 0.171$) and $r = 0.529$ ($p = 0.116$) were observed between SSURGO vs. averaged soil core SIC estimates and averaged vs. interpolated soil core SIC estimates, respectively. Lastly, for the TC estimates, only the correlation between the two field measurement-based approaches was significant ($r = 0.768$, $p = 0.010$); correlations of $r = 0.300$ ($p = 0.399$) and $r = 0.345$ ($p = 0.226$) were observed between

SSURGO vs. averaged soil core TC estimates and SSURGO vs. interpolated soil core TC estimates, respectively.

Our results above contrast with the findings of Zhong and Xu (2011), who reported no significant difference between SSURGO estimates and field measurements of soil organic matter (SOM) based on a paired *t*-test for 30 soil samples in Louisiana ($t = 0.43$, $p = 0.67$). Unlike the glaciated soils of this study, however, the samples examined by Zhong and Xu (2011) were highly organic surface soils from coastal marshlands sampled to a depth of only about 20 cm. Consequently, the coastal marshland soils they studied had SOM levels predominantly in the range from 10 to 80%, whereas the Willsboro Research Farm soils had SOM levels all below 10%.

Estimated soil carbon contents for the three soil orders present on the Willsboro Research Farm can be compared to the midpoint values recently reported by Guo et al. (2006) based on the STATSGO database for all soil orders in the conterminous U.S. For example, Guo et al. reported SOC and SIC contents of 7.5 and 4.3 kg/m², respectively, for Alfisols, 8.0 and 4.8 kg/m², respectively, for Entisols, and 8.9 and 5.1 kg/m², respectively, for Inceptisols. Comparing these reported midpoint values to the various carbon estimates shown in Tables 3, 4 and 5 reveals that generally better agreement is observed with the field-based estimates versus the SSURGO-based estimates. In particular, SSURGO values for the SIC contents of Alfisols and Inceptisols (Table 3) are about 6 and 4.5 times higher, respectively, than the corresponding Guo et al. midpoint values. For Entisols, however, the SSURGO-based estimate in Table 3 is only about two times higher than Guo et al.'s midpoint value.

Estimates of soil carbon storage on the Willsboro Research Farm (Tables 3, 4 and 5) provide an additional indication that the inorganic carbon levels are likely too high in the SSURGO database for these glaciated soils. In many cases, the contribution of SIC to TC storage dominates over the corresponding SOC contribution. For example, the contribution of SIC is more than two times greater than that of SOC for the SSURGO-based estimates for total Alfisols and Inceptisols (Table 3). For the entire farm, the contribution of SIC to TC storage is about two-thirds based on SSURGO estimates. In contrast, the field-based measurements suggest that the SIC contribution to TC storage is only 20%. Because Alfisols make up ~ 64% of the soils present on the farm on an area basis, compared with only ~ 11% for Inceptisols, it is the soil order that most likely leads to the greatest source of error and/or uncertainty in carbon accounting on the farm.

5. Conclusions

This study analyzed differences in glaciated soil carbon estimates at a farm scale using the SSURGO database and detailed field measurements. Based on the results, it can be concluded that detailed site-specific field measurements are more accurate in soil carbon accounting at the soil map unit. SSURGO overestimated SIC and TC contents and storage, but showed somewhat better agreement with field measurements for SOC. As a whole, the extrapolated-with-depth data of SSURGO and scale effects can cause considerable errors in soil carbon estimates at a farm scale, particularly for highly variable soils formed in glacial landscapes. The lack of consistent and significant correlation trends among the different estimation approaches used in the present study highlights the difficulties that must be overcome to generate robust and reliable carbon

estimates in soils dominated by past glacial activity. Detailed site-specific field measurements of soil carbon can enhance SSURGO and improve the accuracy of soil carbon accounting in regional and national carbon balances.

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Fig. 1. Map of Willsboro Farm, NY with the following soil types: Howard gravelly loam, 2 to 8 percent slopes (HgB); Bombay gravelly loam, 3 to 8 percent slopes (BoB); Kingsbury silty clay loam, 0 to 3 percent slopes (KyA); Kingsbury silty clay loam, 3 to 8 percent slopes (KyB); Covington clay, 0 to 3 percent slopes (CvA); Churchville loam, 2 to 8 percent slopes (CpB); Cosad loamy fine sand, 0 to 3 percent slopes (CuA); Claverack loamy fine sand, 3 to 8 percent slopes (CqB); Deerfield loamy sand, 0 to 3 percent slopes (DeA); Stafford fine sandy loam, 0 to 3 percent slopes (StA); Amenia fine sandy loam, 2 to 8 percent slopes (AmB); Massena gravelly silt loam, 3 to 8 percent slopes (McB); Nellis fine sandy loam, 3 to 8 percent slopes (NeB); Nellis fine sandy loam, 8 to 15 percent slopes (NeC).

Fig. 2. Soil organic carbon (SOC) content: a) from SSURGO results averaged over SMUs, b) from soil core sample results averaged over SMUs, and c) interpolated from soil core sample results. In the middle figure only, some SMUs did not have soil cores taken from them and therefore appear as zero in the map (see Table 4).

Fig. 3. Soil inorganic carbon (SIC) content: a) from SSURGO results averaged over SMUs, b) from soil core sample results averaged over SMUs, and c) interpolated from soil core sample results. In the middle figure only, some SMUs did not have soil cores taken from them and therefore appear as zero in the map (see Table 4).

Fig. 4. Soil total carbon (TC) content: a) from SSURGO results averaged over SMUs, b) from soil core sample results averaged over SMUs, and c) interpolated from soil core sample results. In the middle figure only, some SMUs did not have soil cores taken from them and therefore appear as zero in the map (see Table 4).

Fig. 5. Bivariate correlation plots of SOC contents (top), SIC contents (middle) and TC contents (bottom) for field results versus SSURGO results for each SMU.

Fig. 1.

a)

b)

c)

Fig. 2.

a)

b)

c)

Fig. 3.

a)

b)

c)

Fig. 4.

Fig. 5.

Table 1

Soil types within Willsboro Farm.

Soil series (Map unit symbol)	Taxonomic class
<u>Alfisols</u>	
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	Coarse-loamy, mixed, active, mesic Oxyaquic Hapludalfs
Howard gravelly loam, 2 to 8 percent slopes (HgB)	Loamy-skeletal, mixed, active, mesic Glossic Hapludalfs
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	Very-fine, mixed, active, mesic Aeric Endoaqualfs
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	Very-fine, mixed, active, mesic Aeric Endoaqualfs
Covington clay, 0 to 3 percent slopes (CvA)	Very-fine, mixed, active, mesic Mollic Endoaqualfs
Churchville loam, 2 to 8 percent slopes (CpB)	Fine, illitic, mesic Aeric Endoaqualfs
<u>Entisols</u>	
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	Sandy over clayey, mixed, superactive, nonacid, mesic Aquic Udorthents
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	Mixed, mesic Aquic Udipsamments
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	Mixed, mesic Typic Psammaquents
<u>Inceptisols</u>	
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	Coarse-loamy, mixed, active, mesic Aquic Eutrudepts
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	Sandy over clayey, mixed, superactive, mesic Aquic Eutrudepts
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	Coarse-loamy, mixed, active, nonacid, mesic Aeric Endoaquepts
Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	Coarse-loamy, mixed, superactive, mesic Typic Eutrudepts
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	Coarse-loamy, mixed, superactive, mesic Typic Eutrudepts

Table 2

Data sources and descriptions.

Data layer	Description	Source	Resolution/scale
Soil map units	SSURGO database	http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/	1:12,000
Soil sample locations	Point data Coordinates (NAD27 Stat Plane Coordinates System's New York East Zone)	Mikhailova et al., 1996	Sampled on a 137.16 meters square grid
Aerial imagery	Satellite imagery for the world and high-resolution	ESRI World Imagery Map Service	0.3 m

Table 3

Soil carbon inventory by soil type and soil order from SSURGO (2015).

Soil order / Soil series (Map unit symbol, MSU)	Total Area	Total Reported Depth	Mean SOC Content	Mean SIC Content	Mean TC Content	Mean SOC Storage	Mean SIC Storage	Mean TC Storage
	m ²	cm	-----	kg m ⁻²	-----	-----	kg	-----
<u>Alfisols (total)</u>	937940	201 ± 27*	10.40	25.75	36.15	9.76×10⁶	2.41×10⁷	3.39×10⁷
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	183	9.76	21.50	31.26	2.64×10 ⁶	5.82×10 ⁶	8.46×10 ⁶
Churchville loam, 2 to 8 percent slopes (CpB)	36900	183	11.11	32.38	43.49	4.10×10 ⁵	1.19×10 ⁶	1.60×10 ⁶
Covington clay, 0 to 3 percent slopes (CvA)	49076	183	19.44	16.25	35.69	9.54×10 ⁵	7.97×10 ⁵	1.75×10 ⁶
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	183	6.16	10.64	16.80	3.61×10 ⁵	6.24×10 ⁵	9.86×10 ⁵
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	236	10.31	30.06	40.37	4.96×10 ⁶	1.44×10 ⁷	1.94×10 ⁷
Kingsbury silty clay	41990	236	10.31	30.06	40.37	4.33×10 ⁵	1.26×10 ⁶	1.70×10 ⁶

loam, 3 to 8 percent
slopes (KyB)

<u>Entisols (total)</u>	378691	183 ± 0	13.17	8.98	22.15	4.99×10⁶	3.40×10⁶	8.39×10⁶
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	183	10.79	15.71	26.50	6.93×10 ⁵	1.01×10 ⁶	1.70×10 ⁶
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	183	13.05	14.19	27.24	2.20×10 ⁶	2.39×10 ⁶	4.59×10 ⁶
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	183	12.75	0.00	12.75	4.22×10 ³	0.00	4.22×10 ³
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	183	14.36	0.00	14.36	2.09×10 ⁶	0.00	2.09×10 ⁶
<u>Inceptisols (total)</u>	157764	183 ± 0	10.33	23.17	33.50	1.63×10⁶	3.65×10⁶	5.28×10⁶
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	183	9.22	29.78	39.00	2.94×10 ⁴	9.48×10 ⁴	1.24×10 ⁵
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	183	16.64	29.88	46.52	1.41×10 ⁵	2.53×10 ⁵	3.94×10 ⁵

Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	183	9.99	22.63	32.62	3.90×10^5	8.83×10^5	1.27×10^6
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	183	9.99	22.63	32.62	1.07×10^6	2.42×10^6	3.49×10^6

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

Table 4

Soil carbon inventory by soil type and soil order from averaged soil core results (original data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol, MSU)	Total Area	Number of Cores	Core Depth	Mean SOC Content	Mean SIC Content	Mean TC Content	Mean SOC Storage	Mean SIC Storage	Mean TC Storage
	m ²		cm	----- kg m ⁻² -----			----- kg -----		
<u>Alfisols (total)</u>	937940	32	84 ± 29*	10.50**	2.92**	13.42**	9.85×10⁶	2.74×10⁶	1.26×10⁷
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	10	68 ± 37	6.46 ± 3.23	2.50 ± 4.22	8.96 ± 6.15	1.75×10 ⁶	6.76×10 ⁵	2.43×10 ⁶
Churchville loam, 2 to 8 percent slopes (CpB)	36900	n/a***	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Covington clay, 0 to 3 percent slopes (CvA)	49076	1	92	18.90	0.00	18.90	9.27×10 ⁵	0.00	9.27×10 ⁵
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	19	94 ± 19	11.92 ± 3.72	3.62 ± 4.41	15.54 ± 5.79	5.73×10 ⁶	1.74×10 ⁶	7.47×10 ⁶

Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	2	115 ± 5	10.42 ± 6.06	0.96 ± 1.35	11.38 ± 4.71	4.38×10 ⁵	4.01×10 ⁴	4.78×10 ⁵
<u>Entisols (total)</u>	378691	18	84 ± 21	9.12	1.65	10.76	3.45×10⁶	6.25×10⁵	4.07×10⁶
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	4	84 ± 20	11.62 ± 3.97	0.31 ± 0.62	11.92 ± 4.03	7.46×10 ⁵	1.99×10 ⁴	7.66×10 ⁵
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	6	83 ± 31	8.82 ± 3.12	3.50 ± 5.41	12.29 ± 5.56	1.49×10 ⁶	5.90×10 ⁵	2.07×10 ⁶
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	1	91	13.56	0.00	13.56	4.49×10 ³	0.00	4.49×10 ³
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	7	85 ± 15	8.36 ± 3.11	0.11 ± 0.26	8.47 ± 3.29	1.22×10 ⁶	1.56×10 ⁴	1.23×10 ⁶
<u>Inceptisols (total)</u>	157764	4	63 ± 33	8.16^{**}	1.14^{**}	9.31^{**}	1.29×10⁶	1.80×10⁵	1.47×10⁶
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	3	74 ± 31	9.22 ± 3.55	4.28 ± 7.42	13.50 ± 10.54	3.60×10 ⁵	1.67×10 ⁵	5.27×10 ⁵
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	1	30	7.78	0.00	7.78	8.33×10 ⁵	0.00	8.33×10 ⁵

* Means ± standard deviations, unless only one soil core was taken from a specific SMU.

** Reported value omits areas of SMUs from which no soil cores were taken.

*** n/a: not applicable. No soil core was taken from the specific SMU.

Table 5

Soil carbon inventory by soil type and soil order from interpolated soil core results (original data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol, MSU)	Total Area	Mean SOC Content	Mean SIC Content	Mean TC Content	Mean SOC Storage	Mean SIC Storage	Mean TC Storage
	m ²	-----	kg m ⁻² -----		-----	kg -----	
<u>Alfisols (total)</u>	937940	9.96	2.85	12.80	9.34×10⁶	2.67×10⁶	1.20×10⁷
Bombay gravelly loam, 3 to 8 percent slopes (BoB)	270615	7.92	2.48	10.40	2.14×10 ⁶	6.71×10 ⁵	2.81×10 ⁶
Churchville loam, 2 to 8 percent slopes (CpB)	36900	11.51	4.29	15.81	4.25×10 ⁵	1.58×10 ⁵	5.83×10 ⁵
Covington clay, 0 to 3 percent slopes (CvA)	49076	8.33	4.72	13.04	4.09×10 ⁵	2.32×10 ⁵	6.40×10 ⁵
Howard gravelly loam, 2 to 8 percent slopes (HgB)	58680	8.09	0.79	8.84	4.75×10 ⁵	4.64×10 ³	5.19×10 ⁵
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA)	480679	11.46	3.13	14.59	5.51×10 ⁶	1.50×10 ⁶	7.01×10 ⁶

Kingsbury silty clay loam, 3 to 8 percent slopes (KyB)	41990	9.04	1.38	10.42	3.80×10^5	5.79×10^4	4.38×10^5
<u>Entisols (total)</u>	378691	9.37	1.31	10.67	3.55×10^6	4.95×10^5	4.04×10^6
Claverack loamy fine sand, 3 to 8 percent slopes (CqB)	64230	11.00	0.78	11.77	7.07×10^5	5.01×10^4	7.56×10^5
Cosad loamy fine sand, 0 to 3 percent slopes (CuA)	168530	9.04	2.38	11.41	1.52×10^6	4.01×10^5	1.92×10^6
Deerfield loamy sand, 0 to 3 percent slopes (DeA)	331	13.47	0.08	13.55	4.46×10^3	2.65×10^1	4.49×10^3
Stafford fine sandy loam, 0 to 3 percent slopes (StA)	145600	9.02	0.30	9.31	1.31×10^6	4.37×10^4	1.36×10^6
<u>Inceptisols (total)</u>	157764	8.61	2.70	11.30	1.36×10^6	4.26×10^5	1.78×10^6
Amenia fine sandy loam, 2 to 8 percent slopes (AmB)	3185	11.3	4.62	15.92	3.60×10^4	1.47×10^4	5.07×10^4
Massena gravelly silt loam, 3 to 8 percent slopes (McB)	8479	8.22	1.41	9.62	6.97×10^4	1.20×10^4	8.16×10^4

Nellis fine sandy loam, 3 to 8 percent slopes (NeB)	39030	10.54	4.54	15.08	4.11×10^5	1.77×10^5	5.89×10^5
Nellis fine sandy loam, 8 to 15 percent slopes (NeC)	107070	7.86	2.07	9.92	8.42×10^5	2.22×10^5	1.06×10^6