Biogeosciences Discuss., 9, 15175–15211, 2012
www.biogeosciences-discuss.net/9/15175/2012/
doi:10.5194/bgd-9-15175-2012

Biogeosciences
Discussions

The Unified North American Soil Map and its implication on the soil organic carbon stock in North America

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Received: 26 September 2012 – Accepted: 20 October 2012 – Published: 30 October 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Unified North American Soil Map (UNASM) was developed to provide more accurate regional soil information for terrestrial biosphere modeling. The UNASM combines information from state-of-the-art US STATSGO2 and Soil Landscape of Canada (SLCs) databases. The area not covered by these datasets is filled with the Harmonized World Soil Database version 1.1 (HWSD1.1). The UNASM contains maximum soil depth derived from the data source as well as seven soil attributes (including sand, silt, and clay content, gravel content, organic carbon content, pH, and bulk density) for the top soil layer (0–30 cm) and the sub soil layer (30–100 cm) respectively, of the spatial resolution of 0.25° in latitude and longitude. There are pronounced differences in the spatial distributions of soil properties and soil organic carbon between UNASM and HWSD, but the UNASM overall provides more detailed and higher-quality information particularly in Alaska and Central Canada. To provide more accurate and up-to-date estimate of soil organic carbon stock in North America, we incorporated Northern Circumpolar Soil Carbon Database (NCSCD) into the UNASM. The estimate of total soil organic carbon mass in the upper 100 cm soil profile based on the improved UNASM is 347.70 Pg, of which 24.7 % is under trees, 14.2 % is under shrubs, and 1.3 % is under grasses and 3.8 % under crops. This UNASM data will provide a resource for use in land surface and terrestrial biogeochemistry modeling both for input of soil characteristics and for benchmarking model output.

1 Introduction

Analyses of the global carbon cycle suggest a significant role of North America as a biospheric sink of atmospheric carbon dioxide (CO_2) in the overall carbon budget in the world (Prentice, 2001; Gurney et al., 2002; CCSP, 2007). Given the crucial role of North America in global carbon dynamics, North America has become a focus of a US interagency research initiative aimed at quantifying sources and sinks of carbon and the mechanisms underlying continental-scale carbon balance (Wofsy and Harris, 2002). Soil characteristics, an important terrestrial carbon modeling input, affects the modeling results in many aspects. For example, soil texture determines the soil hydrological properties such as soil water holding capacity and wilting point, which in turn control the available water for plants and the transport of water and nutrients within soil. Terrestrial ecosystem models require existing or potential stores of soil nutrients when simulating photosynthesis, respiration, or other biosphere processes (Cramer and Fischer, 1996). Unfortunately, a lack of comprehensive gridded information about North American soil properties based on US and Canadian soil datasets has impeded the understanding and improvement of modeling carbon dynamics in North America. Currently, North American biospheric modeling relies on the spatial subset of different world soil maps, such as digitized Food and Agriculture Organization – United Nations Educational, Science and Cultural Organization (FAO-UNESCO) soil map (Bouwman, et al., 1993; McGuire, et al., 1993), a world dataset of derived soil properties by FAO-UNESCO soil unit for global modeling (Batjes, 1997), the World Inventory of Soil Emission Potentials (WISE) (Gijsman et al., 2007), and the Harmonized World Soil Database (HWSD). The increasing amount of data makes the FAO-UNESCO Soil Map of the World obsolete, but none of the available world soil maps incorporate the more detailed and up-to-date US and Canada soil datasets.

A soil map is usually used to initialize or validate models that study hydrology, evapotranspiration, carbon fluxes, and any applications involving soil moisture. A soil map is also essential to determine soil organic carbon stock, which is the largest pool of terrestrial organic carbon and is affected by land use/land cover change and climate change. Many global and regional soil organic carbon estimates are available (Post et al., 1982; Sombroek et al., 1993; Jobbágy et al., 2000; Tarnocai, 2009). However, few 0.5-degree or finer resolution map of the size and spatial distribution of soil organic carbon pools in North America exist.

This paper describes the development of a two-layer gridded soil attributes dataset in North America for use in biosphere and related modeling. The Unified North American

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Soil Map (UNASM) is compared with the subset of HWSD 1.1 and the differences between these two datasets are evaluated. We also estimate North American soil organic carbon stock based on the NCSCD-modified UNASM and the subset of HWSD 1.1 for major vegetation types, and analyze the spatial distribution of soil organic carbon in North America.

2 Data

The UNASM encompasses the US (including Alaska), Canada, Mexico, and a part of Guatemala. It spans from 84° to 10° latitude, and from −170° to −50° longitude. Below are the descriptions of the source datasets.

2.1 US General Soil Map (STATSGO2)

The US General Soil Map (STATSGO2) was developed by the National Cooperative Soil Survey and supersedes the State Soil Geographic dataset published in 1994. It consists of a broad based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale map (Soil Survey Staff, Natural Resources Conservation Service, http://soildatamart.nrcs.usda.gov). The dataset was created by generalizing more detailed soil survey maps. Where more detailed soil survey maps were not available, data on geology, topography, vegetation, and climate were assembled, together with Land Remote Sensing Satellite (LANDSAT) images. Map unit composition was determined by transecting or sampling areas on the more detailed maps and expanding the data statistically to characterize the whole map unit. The spatial scale of this dataset is 1 : 250 000.

2.2 Soil Landscapes of Canada (SLC) version 3.2 and 2.2

The SLC V3.2 and V2.2 are standardized datasets consisting of the major characteristics of soil and land for Canada. SLCs were compiled at a scale of 1 : 1 000 000, and information is organized according to a uniform national set of soil and landscape criteria based on permanent natural attributes. Each polygon on the map is described by a standard set of attributes and the associated landscape, such as surface form, slope, permafrost and so on. Updates and corrections to boundaries, attributes, and file structures have taken place over the years. SLC V3.2 is the latest revision of the Soil Landscapes of Canada, which was developed by Agriculture and Agri-Food Canada to provide information about the country's agricultural soils and the provincial and national levels (Soil Landscapes of Canada Working Group, 2010). SLC V2.2 is the latest complete coverage of Canada, including areas outside the agricultural regions of the country (Centre for Land and Biological Resources Research, 1996). Both versions of soil landscapes data are linked to Canada soil name and soil layer table V2.0, which contain comprehensive soil attributes along vertical direction for all soils in Canadian National Soil DataBase (NSDB).

2.3 Harmonized World Soil Database (HWSD) version 1.1

The HWSD is a 30 arc-second (ca. 1 km) raster database with over 16 000 different soil mapping units that combines existing regional and national updates of the soil information worldwide (Soil and Terrain Database (SOTER), European Soil Database (ESD), Soil Map of China, World Inventory of Soil Emission Potential database (WISE)) with the information contained within the 1 : 5 000 000 scale FAO-UNESCO soil map of the world (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2013). The soil-mapping-units raster layer can be linked to harmonized attribute data, which contains 16 physical and chemical soil properties. The HWSD contains two standard depths – the top soil layer ranges from 0 to 30 cm and the sub soil layer ranges from 30 to 100 cm.

HWSD 1.1 provides reference bulk density values, which are calculated from equations developed by Saxton et al. (1986) that relate to the soil texture only (FAO/IIASA/ISRIC/ISSCAS/JRC, 2011). These estimates, although generally reliable, overestimate the bulk density in soils that have a high porosity (Andosols) or that are high in organic matter content (Histosols) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2013).

Therefore, we corrected the bulk density values of these two soil types using the corresponding average values from WISE.

2.4 The Northern Circumpolar Soil Carbon Database (NCSCD)

One of the important objectives of this study is to quantify the soil organic carbon storage in North America. However, none of the datasets described above provide sufficient and accurate soil organic carbon information for the high-latitude permafrost region. To provide a more accurate estimate of the soil organic carbon storage in North America, we combined the NCSCD with soil organic carbon content derived from the UNASM.

The NCSCD was developed to quantify the soil organic carbon stocks in the circumpolar permafrost region (18.7×10^6 km^2). The NCSCD links organic carbon measurements from 1647 pedons in the northern permafrost regions to several digitized regional/national soil maps to produce a combined circumpolar coverage (Hugelius et al., 2012). Together these datasets have been used to quantify soil organic carbon stock in the top soil layer (0–30 cm depth) and down to a depth of 1m. The NCSCD provides both GIS-polygon files and gridded datasets. As the spatial resolution of the UNASM is 0.25°, we used the 0.25-degree gridded NCSCD (in NetCDF format) in this study for estimating North American soil organic carbon stock.

3 Methods and procedures

STATSGO2 and SLCs provide more detailed and accurate soil information than HWSD. However, STATSGO2 and SLCs are not easy for biospheric modelers to use directly. First, many biospheric and related models require a uniform grid cell or raster format different from the format of STATSGO and SLCs, which are defined as polygons in a vector geographic information system environment. Second, the number, thickness, and depth of soil layers vary widely from one soil component to another, but most models need soil data with harmonized layers that have uniform depths. Third, the location information is not provided for each component, and only the relative amount of each component within a map unit is specified. Consequently, our objective is to produce a gridded soil map that would meet the needs of modelers, combining information of STATSGO2 and SLCs and filling the rest of the area with HWSD1.1.

The compilation of the UNASM required a marked degree of data integration and generalization of the geographical distribution of soil types to a regionally representative pattern. Developing the UNASM involved four stages:

1. Convert STATSGO2, SLCs, and HWSD 1.1 into 0.25° gridded format by selecting the dominant soil type in each cell.
2. Merged STATSGO2, SLCs and HWSD1.1 into a seamless map that can best represent soil in North America.
3. Harmonize the North American soil map developed in stage 2 into two standard layers, 0–30 cm and 30–100 cm.
4. Quality control.

3.1 Stage I: convert STATSGO2, SLCs, and HWSD 1.1 into 0.25° gridded format

For both STATSGO2 and SLCs, the required soil properties were linked to the soil maps, which contain polygon features of soil and nonsoil map units on the landscape. Each 0.25-degree grid cell may overlap with one or more soil unit polygon features and each of these soil unit polygon features may contain one or more soil components, such as sand/silt/clay fractions and bulk density. We first evaluated all the unique soil types and their combined area fractions in a 0.25-degree cell. The soil type with the highest area fraction was selected as the dominant soil type in the cell. We then selected the soil component that has the largest area of the dominant soil type. Last, the selected soil component's vertical soil layers information along with their detailed soil properties were assigned to the target 0.25-degree grid cell. The data structure of HWSD 1.1

is similar to those of STATSGO2 and SLCs. The difference is that the HWSD 1.1 is represented in a 30 arc-second resolution raster map instead of vector polygons. We applied a similar approach to that used for the two polygonal datasets to select the dominant soil type and soil component for each target 0.25-degree cell and then linked to the detailed soil attributes.

3.2 Stage II: integrating different soil datasets into a seamless product

The gridded STATSGO2, SLCs and HWSD 1.1 were integrated into a 0.25-degree North American grid with a total of 142 080 grid cells. Based on the quality of the different data sources, we merged these soil data with the following priority: STATSGO2 > SLC 3.2 > SLC 2.2 > HWSD 1.1. The aim was to take advantage of more precise soil information from STATSGO2 and SLCs, and fill the rest of the area with the HWSD 1.1. The source dataset used by each cell can be traced back using the source code variable. Figure 1 illustrates the spatial distribution of data sources for the UNASM. Among all the cells that have valid values, STATSGO2 accounts for 36 % of cells, SLC3.2 and SLC2.2 accounts for 8 % and 4.5 % respectively, and HWSD 1.1 accounts for 51.5 % of cells.

3.3 Stage III: harmonization with depth

After integrating the different soil datasets together, the seamless dataset from Stage II still has inconsistent vertical soil layers. Grid cells assigned with soil properties from STATSGO2 may contain up to 11 soil layers, those from SLCs may contain up to 9 soil layers and cells from HWSD have two soil layers. The thickness of soil layers also varies across cells. To harmonize the vertical structure within these three datasets in the UNASM, we converted the profile data into two standard layers that are consistent with the HWSD 1.1. The top layer is from 0 to 30 cm and the sub layer is from 30 to 100 cm.

We used the depth-weighted averaging method to interpolate the layers from the Stage II dataset to the two standard layers for the volume-related properties (gravel fraction and pH), and used the mass-weighted averaging method for the other soil properties that are related to soil weight. The standard UNASM layers were compared to each layer in the Stage II soil dataset. If the UNASM layer was entirely contained within a single unified soil data layer from Stage II, we used the Stage II layer value for the standard layer. Otherwise, all layers from Stage II that were fully or partially included within the standard UNASM layers were identified, and a portion to each of the standard layers was used as the weighting to determine the standard layer properties. If the soil thickness is less than 30 cm or 100 cm, the maximum soil depth would be used for harmonization rather than extending the attributes to 100 cm. Therefore, if the soil thickness was less than 30 cm, the weighted average of soil properties in different layers would be assigned to the top soil layer, but the sub soil layer (30–100 cm) would be filled with missing value, which is −999.0 in this study. The maximum soil depth derived from the data sources is kept as a separate variable in the UNASM.

3.4 Stage IV: quality control

All fields in the UNASM were checked for the minimum and the maximum, which were then compared to the value range for each soil property in the source datasets. The cell values in the UNASM falling out of soil property value ranges were treated as errors. Only few errors were found, and these errors have been corrected.

Missing values resulting from empty entries in the data source were filled with −999.0, except for soil texture fields in the surface organic layer. Zeros in sand, silt, clay content in the surface organic layer from STATSGO2 and SLCs are valid values for soil since soil texture is not applicable in this case.

The sum of sand, silt and clay fractions in top and sub soil layers was corrected to 100 % in the cases where necessary due to rounding errors. Similar to what was done in the development of the HWSD 1.1, when the sum was less than 100 %, the largest percentage was increased to obtain 100 %. When the sum exceeded 100 %, the highest value was reduced to obtain a sum of 100 %.

3.5 Soil properties

This study considers seven soil attributes that are commonly required in terrestrial biosphere modeling studies (Table 1). In addition, we provide the maximum soil depth from the sources and the source code that specifies the origin of the attributes values. The detailed explanations of each soil property can be found in the Appendix A.

3.6 Computation of soil carbon content and soil carbon mass

The soil organic carbon content (SOCC, $\mathrm{g\,cm^{-2}}$) was calculated for each cell of the UNASM using the formula:

$$\mathrm{SOCC} = \mathrm{OC} \times \mathrm{BD} \times T \times (1 - \mathrm{Gravel}) \tag{1}$$

where OC is the soil organic carbon concentration (% weight), BD is the bulk density ($\mathrm{g\,cm^{-3}}$), T is the soil layer thickness (either 30 or 70 cm), and Gravel is the gravel fraction (% volume). Using this information, the SOCC was calculated for the 0–30 and 30–100 cm layers for all cells. The total SOCC of the upper 100 cm soil profile is the sum of SOCC in the top soil and sub soil layers. To provide a more detailed estimate of soil organic carbon, the SOCC values in the high-latitude cells in the UNASM were then replaced by the SOCC values in the corresponding cells in the 0.25-degree NCSCD. The soil organic carbon mass (SOCM, Pg) was determined by multiplying the SOCC by the area of each cell.

4 Results

4.1 The comparisons of soil properties between UNASM and HWSD

Figure 2 shows the histogram of soil property values in the top soil layer (0–30 cm) and the sub soil layer (30–100 cm) in the UNASM and HWSD. Overall, the distribution of soil property values in the UNASM agrees with those in the HWSD, but the distributions of gravel fraction, organic carbon concentration, and bulk density have greater discrepancies between the UNASM and the HWSD. The UNASM has higher gravel fraction, with 56 % non-zero cells within 10–100 % value range in the top-soil layer and 68 % of non-zero cells in the sub soil layer. In contrast, the HWSD only has 45 % of non-zero cells lie within 10–100 % value rang in the top soil layer and 56 % in the sub soil layer. The UNASM also has higher organic carbon concentration. The maximum soil organic carbon concentration in the UNASM is 58 % in the top soil layer and 60 % in the sub soil layer, but in the HWSD the maximum is 38 % in the top soil layer and 39 % in the sub soil layer. In the top soil layer, 13 % of non-zero cells in the UNASM lie within 5–60 % value range while only 6 % of non-zero cells in the HWSD lie within the same high value range. Both STATSGO2 and SLCs contain the organic layer, the O horizon in the soil profile. When harmonizing the unified data into two standard layers, we combined organic layer with the mineral layers below. Usually the organic layer did not extend past the top 30 cm, so the top soil layer only was affected, resulting in the higher soil organic carbon concentration in the UNASM. However, occasionally, the organic layer extends below 30 cm depth, affecting the density of both top and sub soil layer in the UNASM. Unfortunately, there is no information available about whether the HWSD takes into account the organic layer during harmonization. Because of the higher soil organic carbon concentration, the UNASM has lower bulk density than the HWSD, with a mean of 1.2 $\mathrm{g\,cm^{-3}}$ in the top soil layer and 1.3 $\mathrm{g\,cm^{-3}}$ in the sub soil layer.

The difference map, which is the result of UNASM minus HWSD, demonstrates the spatial distributions of differences between the UNASM and the HWSD for all soil properties (Fig. 3).

Soil Texture Although the histogram of soil texture in the UNASM are close to those in the HWSD, the maps (Fig. 3) illustrate the pronounced differences in the spatial distribution of soil texture in these two datasets. For example, the UNASM has lower sand content in the Central and Eastern US, Alaska, and some areas in Canada, but higher sand content in the coastal area of Southeastern US and the areas near Great Slave Lake and Lake Winnipeg in Canada. Clay content in general is slightly lower in the UNASM. The locations of high clay content are in the north of Lake Winnipeg (Canada), along the Mississippi River (US), and in Central Montana (US). The difference in spatial distribution of soil texture would affect the hydrological properties of soil, such as porosity and hydraulic conductivity, and hence influence the modeling of water availability and energy partitioning.

Gravel Fraction Gravel fraction is much higher in the Western and Northeastern US, some areas of Alaska, and Southwestern Canada in the UNASM. We compared the gravel fractions derived from these two datasets with the data reported in a few studies. In the North-Western Sonoran Desert, California, Young and Nobel (1986) reported that the average gravel content from 0–50 cm is about 35 % in the study sites. In the UNASM, the gravel fraction in Sonoran Desert ranges from 22 % to 51 %, but the HWSD only has 4 % gravel fraction in the same area. Simanton et al. (1994) reported up to 60 % gravel in the upper 10 cm of the soil profiles and less than 40 % gravel in the underlying parts of the profiles in the study sites in Southeastern Arizona. In the same area, gravel fraction in the UNASM ranges from 6.8 % to 51 %, but in the HWSD it ranges from 4 % to 20 %. Vasek (1980) reported 24 %–57 % gravel in the study sites in the San Bernardino County of Mojave Desert, California. In the UNASM, the gravel fraction is between 9 % and 51 %, but in the HWSD, the gravel fraction is between 4 % and 20 % in the same area. The gravel fraction data provided in a few studies suggest that the HWSD may underestimate the gravel fraction in Western US.

Soil Organic Carbon Concentration The UNASM has much higher soil organic carbon concentration in most area of Alaska, and the lake area in the Central Canada, but slightly lower values in the conterminous US for the top soil layer. A few studies reported the soil organic carbon concentration and bulk density of the soil samples taken at sites in Alaska (Table 2). With these data, we calculated the soil organic carbon concentration and bulk density for the surface layer (0–30 cm) and the sub soil layer (30–100 cm) using the same method as we used for UNASM. In the UNASM, soil organic carbon concentration values range from 0.87 to 51 % and the median is 17 % in Alaska, which agrees well with the field studies data listed in Table 2. This qualitative comparison suggests that the HWSD may underestimate the soil organic carbon concentration in Alaska.

pH We compared the pH values in the UNASM and the HWSD with the median pH values provided in Soil Test Levels in North America (Fixen, 2005). We found that both datasets agree well with values in Fixen's report, but pH in the UNASM is slightly lower than pH in the HWSD in most areas of Southwestern Canada, Alaska, and some areas of US, while slightly higher in Southwestern and Southeastern US.

Bulk Density Bulk density diverges from HWSD to a greater degree than for the other soil properties. The UNASM bulk density is the mass-weighted average and includes the soil organic layer as part of the profile. In the area filled with the values from HWSD, bulk density is also recalculated using our method. The values in the area filled with the HWSD are slightly lower than the values in the original HWSD. The most significant differences of bulk density lie in Alaska, US and Northern Alberta and Southern Northwest Territories, Canada. Where the soil organic carbon concentration is higher in the UNASM, the bulk density is lower than in the HWSD.

4.2 Spatial distribution of SOCC

Regional patterns of soil carbon content from 0–100 cm based on the NCSCD, UNASM, and HWSD are shown in Fig. 4. The UNASM provides more details in conterminous US than HWSD does, particularly showing higher values in Central US, the coastal area of Washington state, Minnesota, coastal area of North Carolina, and Southern Florida. In northern circumpolar region, all three maps demonstrate the high SOCC in coastal area of Ontario, Manitoba and around Great Bear Lake, Great Slave Lake and Lake Winnipeg in Canada. However, the NCSCD provides pronounced details of SOCC distribution in Canada especially in Northern Canada where both UNASM and HWSD lack data.

Interestingly, the estimate based on the original UNASM shows higher SOCC in Alaska than that in NCSCD does. In Alaska, SOCC derived from the UNASM ranges from 1.5–8.1 $\mathrm{g\,cm^{-2}}$ in the northern tundra zone, to 3.7–7.1 $\mathrm{g\,cm^{-2}}$ in the interior of Alaska, and 0.67–9.6 $\mathrm{g\,cm^{-2}}$ in the southern coastal area, but in the NCSCD SOCC value ranges from 1.0–8.3 $\mathrm{g\,cm^{-2}}$ in the northern tundra zone, to 0.6–2.6 $\mathrm{g\,cm^{-2}}$ in the interior of Alaska, and 0.60–9.6 $\mathrm{g\,cm^{-2}}$ in the southern coastal area. The estimate derived from the UNASM roughly agrees with the field sampling result of Ping et al. (1997), in which they reported soil carbon content of 6.92, 5.99, and 3.14 $\mathrm{g\,cm^{-2}}$ respectively in three tundra vegetation zones in Northern Alaska, 7.87, 1.69, and 12.92 $\mathrm{g\,cm^{-2}}$ in the interior forest/taiga zone, and 2.4, 12.6, and 4.37 $\mathrm{g\,cm^{-2}}$ in the southern coastal zone. However, Ping et al. (1997) also mentioned in the paper that their result was slightly higher than other studies (Oechel and Billings, 1992; Chapin and Matthews, 1993). The HWSD has much lower SOCC values in Alaska mainly due to insufficient data. To provide a more detailed estimate of soil organic carbon stock in North America, we incorporated the Alaska and Canada soil organic carbon data of NCSCD into the SOCC map derived from the UNASM. The NCSCD-modified UNASM soil organic carbon map is only different from the original UNASM in Alaska and Canada where the UNASM was developed without sufficient data, and thus the rest of the analyses use the NCSCD-modified UNASM soil organic carbon map instead.

Figure 5 illustrates the mean SOCC within each degree latitudinal band for the upper 30 cm and the upper 100 cm soil profile. The NCSCD-modified UNASM soil organic carbon map shows significantly high values within 65°–80° latitudinal bands where the permafrost soil in Alaska and Canada is high in soil organic carbon. The relatively high potential for organic matter storage in cool and humid high latitudinal soils is mainly due to climatic conditions that cause the slow decomposition rate in the balance between carbon inputs and carbon losses (Post et al., 1982; Carter et al., 1997). However, the HWSD illustrates low values in this region due to insufficient data, but shows a peak in 48°–58° latitudinal bands.

Within 48°–25° latitudinal band, the NCSCD-modified UNASM soil organic carbon map is the same as the original UNASM, which is mainly derived from STATSGO2. In this region, the UNASM has lower average SOCC in the top soil layer due to the high gravel fraction, but little discrepancy from the pattern of the HWSD in the upper 100 cm soil profile. Although soil organic carbon concentration, bulk density, and gravel fraction show pronounced regional differences between UNASM and HWSD within the 48°–25° latitudinal bands, the combined effect of these three properties diminishes the differences in the SOCC in the upper 100 cm soil profile. The increase in SOCC within 21°–19° latitudinal bands is the result of relatively higher SOCC in Central and Southeastern Mexico.

4.3 SOCC summarized by vegetation types

Although the spatial distribution of soil organic carbon is primarily controlled by precipitation, temperature and clay content (Oades, 1988; Sala et al., 1988; Amundson, 1989; Paul, 1984), the type of vegetation or crop and the type of land use or agricultural management system can also influence soil organic matter content (Carter et al., 1997). We calculated the average SOCC for major vegetation types (Fig. 6), including needle leaf trees, broad leaf trees, mixed trees, shrubs, grasses, and crops, based on the International Satellite Land Surface Climatology Project (ISLSCP II) MODIS (Collection 4) IGBP Land Cover, 2000–2001 (Friedl et al., 2002, 2010). Needle leaf tree has the highest average SOCC as the result of slow decomposition under cool temperatures at high latitudes. Broad leaf trees, on the other hand, have lower average SOCC. Shrubs have higher SOCC in the NCSCD-modified UNASM soil carbon map than those in the HWSD, mainly because the shrubs not only live in the mid-latitude semi-arid and arid areas but also exist in high-latitude areas, where there are a large amount of organic carbon in soil. Grasses have the lowest average SOCC values in NCSCD-modified UNASM. Crops have lower average SOCC values than needle trees and mixed trees but have higher values than grasses. However, there are very few studies of the vegetation impact on the spatial distribution of soil organic carbon, because vegetation and climate typically covary in a complex fashion. Post et al. (1982) estimated soil carbon density for vegetation life zones and studied its relationship with climatic factors. Quideau et al. (2001a,b) suggested that the mosaic of vegetation has significant impact on the accumulation and turnover of soil organic matter directly by determining the quality and the pathway of biomass incorporation into soil.

4.4 SOCM

In the NCSCD-modified UNASM soil carbon map, the total SOCM in the upper 100 cm soil profile is 347.70 Pg, and in the HWSD, the total SOCM is 276.46 Pg (Fig. 7). About 42.6 % of the carbon pool in the NCSCD-modified UNASM soil carbon map and 54.4 % of the carbon pool in the HWSD are held in the top 30 cm, the layer which is most prone to changes upon land use/land cover conversion. The NCSCD-modified UNASM has lower carbon mass in the surface soil layer than the HWSD because of higher gravel fraction in the top soil layer in the UNASM and the higher soil organic carbon stock in the deep soil profile in the permafrost region. Table 3 summarizes the SOCM for six major vegetation types, including needle trees, broad leaf trees, mixed trees, shrubs, grasses, and crops. The upper 100 cm soil under needle trees stores about 70.80 Pg carbon mass based on the NCSCD-modified UNASM, and the soil under shrubs is the second largest carbon pool that stores about 49.26 Pg carbon. Based on the estimates from the NCSCD-modified UNASM soil organic carbon map, about 24.7 % of soil organic carbon in the upper 100 cm is stored under trees, about 14.2 % of soil organic carbon is stored under shrubs, and only 1.3 % is stored under grasses and 3.8 % under crops.

5 Discussion

5.1 The difference between UNASM and HWSD

We present the 0.25-degree Unified North American Soil Map that combines US STATSGO2, Canada SLC3.2 and SLC2.2, and HWSD1.1. The HWSD is the most recent soil dataset, but to our knowledge it is based on measurements from North America that were made in the 1970s. Therefore the UNASM provides more up-to-date and detailed information for the US and Canada. The pronounced difference between UNASM and HWSD occurs in Alaska and Central Canada around the major lakes. The difference between UNASM and HWSD in conterminous US is less obvious than that in Alaska, US and some areas in Canada, but the difference, especially in soil texture and soil organic carbon concentration, may result in the large differences in estimating water and energy budgets and SOCM (Fernandez-Illescas et al., 2001; Abu-Hamdeh, 2003). Further studies are needed to evaluate the impact of different soil input data in the model simulations.

The UNASM is created for use in terrestrial biosphere modeling. Given the limited resources, the UNASM is developed at 0.25° in latitude and longitude, which limits the flexibility for users to downscale to any spatial resolution. Moreover, the UNASM is derived from different sources that use different soil taxonomies, and thus the current version of the UNASM does not provide a uniform soil taxonomy. There are currently no quantitative measures of the uncertainty associated with the UNASM. Based on the source data quality, we have relatively higher confidence in the area based on STATSGO2 and SLC3.2, and lower confidence in the area based on SLC2.2 and the area filled with HWSD1.1.

5.2 The implication on North American soil organic carbon stock

Both UNASM and HWSD lack sufficient data in high latitudes, particularly in Northern Canada, where contains a significantly large amount of soil organic carbon in permafrost soils (Tarnocai et al., 2009). To provide more accurate and up-to-date estimate of soil organic carbon stock in North America, we incorporated Alaska and Canada NCSCD into UNASM soil organic carbon map. The NCSCD-modified UNASM soil organic carbon map demonstrates more details in the spatial distribution of SOCC and the large potential of soil organic carbon stock in high latitudinal regions. However, the NCSCD-modified UNASM soil organic carbon map has lower values in Alaska than the SOCC derived from the original UNASM. The average SOCC in the upper 100 cm in Alaska is 4.0 $\mathrm{g\,cm^{-2}}$ based on the UNASM and 1.8 $\mathrm{g\,cm^{-2}}$ based on the NCSCD-modified UNASM. The average SOCC estimated from NCSCD-modified UNASM is also lower than the other published estimates. For example, Post et al. (1982) reported an average SOCC value of 2.18 $\mathrm{g\,cm^{-2}}$ for the Arctic tundra region. Ping et al. (2008) reported average SOCC to be 3.48 $\mathrm{g\,cm^{-2}}$ for 100 cm depth in Alaska. Johnson et al. (2011) stratified the state of Alaska into different ecoregions and reported average SOCC (for 100 cm depth) of 5.33 $\mathrm{g\,cm^{-2}}$, 0.86 $\mathrm{g\,cm^{-2}}$, 2.1 $\mathrm{g\,cm^{-2}}$, and 2.4 $\mathrm{g\,cm^{-2}}$ for arctic tundra, intermontane boreal, Alaska range transition, and costal rainforests respectively. Mishra and Riley (2012) predicted SOCC in Alaska using spatially referenced environmental variables and pedon observations, resulting in the average SOCC of 3.54 $\mathrm{g\,cm^{-2}}$ for the active layer and 5.36 $\mathrm{g\,cm^{-2}}$ for the whole profile. The average SOCC estimated from the original UNASM is close to the case 3 (4.49 $\mathrm{g\,cm^{-2}}$) result reported by Bliss and Maurestter (2010), probably because both the UNASM and the case 3 in Bliss and Maurestter (2010) used the soil order to link STATSGO soil map with soil property information. The differences with the estimates of Alaska average SOCC from these studies can be attributed to the number and quality of the pedon observations used to develop the dataset, the way to develop the soil map and estimate SOCC, and the spatial resolution of the soil map. The total SOCM across Alaska is 48.07 Pg based on the UNASM and 24.52 Pg based on the NCSCD-modified UNASM soil organic carbon map. In the conterminous US, the SOCC derived from the UNASM agrees with the one based on HWSD in most areas, except in the Eastern US Minnesota, and

Iowa. The UNASM shows lower SOCC in Eastern US, but higher SOCC in Minnesota and Iowa.

The average SOCC for the major biome types in the NCSCD-modified UNASM roughly agrees with the result of Post et al.'s (1982) study, except shrubs in NCSCD-modified UNASM have much higher SOCC values than the cool temperate bush in Post et al.'s (1982) study. Needle trees have higher mean SOCC than the other vegetation types mainly due to the cool weather that results in the slow decomposition. Given the limited studies of the impact of vegetation on soil organic carbon spatial distribution, our results can only be explained by the climate factors, but more studies on finer scales are needed to evaluate the effect of vegetation on soil organic carbon spatial distribution under the same climatic condition.

The total SOCM in the upper 100 cm soil profile is 347.70 Pg based on the NCSCD-modified UNASM, higher than the estimates of 276.46 Pg from the HWSD. Since the NCSCD does not provide other soil properties information required for terrestrial biosphere modeling except for SOCC, the NCSCD-modified UNASM soil organic carbon map is a separated dataset from the UNASM. It provides the most accurate and up-to-date spatial distribution of SOCC in North America and can be used as a benchmark for the terrestrial biosphere modeling research.

6 Conclusions

The North American soil map presented here fills a need of the modeling community for a dataset of soil physical properties specifically created for North America by combining state-of-the-art soil information from STATSGO2, two versions of SLCs, and HWSD1.1. The comparison between the UNASM and the HWSD illustrates the pronounced difference in the spatial distributions of soil properties and soil organic carbon, but the UNASM overall provides higher-quality and more detailed information particularly in Alaska and Central Canada. The total SOCM in the upper 100 cm soil profile is 347.70 Pg based on the NCSCD-modified UNASM, among which 24.7 % is under trees, 14.2 % is under shrubs, and 1.3 % is under grasses and 3.8 % under crops. These new estimates will help to provide a more reliable prediction for the effect of global climate change and land use management on the carbon budget.

In order to provide end users the most functional dataset, the UNASM is in uniform 0.25-degree grid. The UNASM is in NetCDF format to meet the input requirement of most terrestrial biosphere models. This data will be archived in Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (ORNL DAAC) (Liu et al., 2012).

Appendix A

The description of soil properties in the UNASM

A1 Sand, silt, and clay content

Sand, silt, and clay content, defined as the percentage of each size class based on weight, are the most important soil attributes to quantify soil texture. Sand comprises particles or granules ranging in diameter from 0.0625 mm to 2 mm. Sands are mineral particles between 0.05 mm and 2.0 mm. Silt size is between 0.002 and 0.0625 (in STATSGO2, the silt size is between 0.002 and 0.05 mm). Clay is composed primarily of fine-grained with the diameter less than 0.002 mm.

When harmonizing the unified soil dataset into two standard layers (the topsoil layer is from 0–30 cm, and the subsoil layer is from 30–100 cm), sand, silt and clay fractions were calculated as:

$$\text{Sand, Silt, Clay\%} = \frac{M_{\text{sand, silt, clay}}}{M_{\text{min}}} \times 100\,\% \tag{A1}$$

where $M_{\text{sand, silt, clay}}$ represents the mass of sand, or silt or clay in the standard layer, and M_{min} represents the total mass of mineral soil in the standard layer. M_{min} is determined as the product of the bulk density of mineral soil, the fraction of mineral soil (which is 1 minus the fraction of the organic matter), and the volume of the standard soil layer.

A2 Gravel content

Gravel content is the volume percentage gravel (diameter > 2 mm) in the soil. The depth-weighted average method was used to interpolate gravel content of different layers into two standard layers in the UNASM.

A3 Bulk density

Bulk density is the ratio of the mass of soil material to the total volume of solids plus pores. It is often used to estimate soil hydrological properties and to calculate the total amount of soil carbon. The reference bulk density measured at 0.33 bar water confront from STATSGO2 is used for the UNASM. Since bulk density are measured and estimated using different methods, potential bias among the bulk density measurements from different sources might exist.

When harmonizing the unified soil dataset into two standard layers, bulk density is calculated as:

$$\mathrm{BD} = \frac{M_{\mathrm{org}} + M_{\mathrm{min}}}{V} \qquad \text{(A2)}$$

where M_{org} and M_{min} are the mass of organic matter and mineral matter in the standard soil layer, and V is the volume of the standard layer. M_{org} is determined as the product of bulk density of organic matter, the fraction of organic matter, and the volume. M_{min} is determined as the product of the bulk density of mineral soil, the fraction of mineral soil (which is 1 minus the fraction of the organic matter), and the volume.

A4 Soil organic carbon

Soil organic carbon concentration is defined as the percentage of soil weight. However, estimates of soil organic carbon stock generally refer to a given depth of soil. Therefore the amount of soil in a given depth depends not only on soil organic carbon content as provided by this dataset, but also depends on bulk density, area, and depth.

The mass-weighted average of soil organic carbon concentration (OC) was calculated when the unified soil dataset was harmonized into two standard layers:

$$\mathrm{OC} = 0.58 \times \frac{M_{\mathrm{org}}}{M_{\mathrm{org}} + M_{\mathrm{min}}} \times 100 \tag{A3}$$

where M_{org} and M_{min} are the mass of organic matter and mineral matter respectively, the same as the ones used to calculate bulk density. The constant 0.58 in the above equation assumes that soil organic carbon accounts for 58 % of soil organic matter (Mann, 1986).

A5 pH

pH is a measure for the acidity and alkalinity of the soil. In the HWSD, pH is measured in a soil-water solution. However, in SLCs, pH is measured in calcium chloride ($CaCl_2$). In STATSGO2, pH is measured in both ways. To keep the consistency with HWSD, we use pH measured in H_2O in the UNASM. Miller and Kissel's (2010) study demonstrated that pH measured in H_2O is significantly linearly related with pH measured in $CaCl_2$, only slightly diverging from the 1 : 1 line. The depth-weighted average method was used to interpolate pH values of different layers into two standard layers in the UNASM.

A6 Soil depth

Soil depth here is the maximum soil depth of each cell before harmonization to standard layers. Maximum soil depth can be used as the approximate measure of the depth-to-bedrock. However, in the HWSD, the maximum soil depth is either 30 cm or 100 cm, which cannot represent the soil thickness in most cells.

Acknowledgements. The authors would like to acknowledge the financial support from the NASA's Terrestrial Ecology Program (TEP) for the Modeling and Synthesis Thematic Data Center (MAST-DC: project 09-TE09-26). We would like to thank the core group from the NASA TEP-funded Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) for providing helpful suggestions to this study. This study was part of the North American Carbon Program.

References

Abu-Hamdeh, N. H.: Thermal properties of soils as affected by density and water content, Biosyst. Eng., 86, 97–102, 2003.

Amundson, R. G., Chadwick, O. A., and Sowers, J. M.: A comparison of soil climate and biological activity along an elevational gradient in the Eastern Mojave Desert, Oecologia, 80, 395–400, 1989.

Batjes, N. H.: A world dataset of derived soil properties by FAO-UNESCO soil unit for global modeling, Soil Use Manage., 13, 9–16, 1997.

Bliss, N. and Maursetter, J.: Soil organic carbon stocks in Alaska estimated with spatial and pedon data, Soil Sci. Soc. Am. J., 74, 565–579, 2010.

Bouswman, A. F., Fung, I. E., and Matthews, J. J.: Global analysis of the potential for N_2O production in natural soils, Global Biogeochem. Cy., 7, 557–597, 1993.

Carbon Cycle Science Program (CCSP) The First State of the Carbon Cycle Report (SOCCR): The Northma American Carbon Budget and Implications for the Global Carbon Cycle. A report by the US Climate Change Science Program and the Subcommitte on Global Change Research, edited by: King, A. W., Dilling, L., Zimmerman, G. P., Fairman, D. M., Houghton, R. A., Marland, G., et al., National Oceanic and Atmospheric Administration, National Climate Data Center, Asheville, NC, USA, 242 pp., 2007.

Centre for Land and Biological Resources Research: Soil Landscapes of Canada, v.2.2, Research Branch, Agriculture and Agri-Food Canada, Ottawa, 1996.

Chapin III, F. S. and Matthews, E.: Boreal carbon pools: approaches and constraints in global extrapolations, in: Proceedings of the International Workshop on Carbon Cycling in Boreal

Forest and Sub-arctic Ecosystems: Biospheric Responses and Feedbacks to Global Climate Change, Corvalis, Oregan, US, 9–20, 1993.

Cramer, W. and Fischer, A.: Data requirements for global terrestrial ecosystem modeling, in: Global Change and Terrestrial Ecosystem, Cambridge University, Cambridge, UK, 532–534, 1996.

FAO/IIASA/ISRIC/ISS-CAS/JRC: Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria, 2011.

Fernandez-Illescas, C. P., Porporato, A., Laio, F., and Rodriguez-Iturbe, I.: The ecohydrological role of soil texture in a water-limited ecosystem, Water Resour. Res., 37, 2863–2872, 2001.

Friedl, M. A., McIver, D. K., Hodges, J. C. F., Zhang, X. Y., Muchoney, D., Strahler, A. H., Woodcock, C. E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., and Schaaf, C.: Global land cover mapping from MODIS: algorithms and early results, Remote Sens. Environ., 83, 287–302, 2002.

Friedl, M. A., Strahler, A. H., and Hodges, J.: ISLSCP II MODIS (Collection 4) IGBP Land Cover, 2000–2001, in: ISLSCP Initiative II Collection. Data set, edited by: Hall, F. G., Collatz, G., Meeson, B., Los, S., Brown de Colstoun, E., and Landis, D., available at: http://daac.ornl.gov/, last access: 16 September 2012, Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA, doi:10.3334/ORNLDAAC/968, 2010.

Gijsman, A. J., Thornton, P. K., and Hoogenboom, G.: Using the WISE database to parameterize soil inputs for crop simulation models, Comput. Electron. Agr., 56, 85–100, 2007.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksyutov, S., Masarie, K., Peylin, P., Prather, M., Pak, B. C., Randerson, J., Sarmiento, J., Taguchi, S., Takahashi, T., and Yuen, C.-W.: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, Nature, 415, 626–630, 2002.

Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P., and Swanson, D. K.: The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, Earth Syst. Sci. Data Discuss., 5, 707–733, doi:10.5194/essdd-5-707-2012, 2012.

Janzen, H. H., Campbell, C. A., Izaurralde, R. C., Ellert, B. H., Juma, N., McGill, W. B., and Zentner, R. P.: Management effects on soil C storage on the Canadian prairies, Soil Till. Res., 47, 181–195, 1998.

Jobbágy, E. G. and Jackson, R. B.: The vertical distribution of soil organic carbon and its relation to climate and vegetation, Ecol. Appl., 10, 423–436, 2000.

Johnson, K. D., Harden, J., McGuire, A. D., Bliss, N. B., Bockhelm, J. G., Clark, M., Mettleton-Hollingsworth, T., Jorgenson, M. T., Kane, E. S., Mack, M., O'Donnell, J., Ping, C. E., Schuur, A. G., Turetsky, M. R., and Valentine, D. W.: Soil carbon distribution in Alaska in relation to soil-forming factors, Geoderma, 167, 71–84, 2011.

Kane, E. S., Valentine, D. W., Schuur, E. A., and Dutta, K.: Soil carbon stabilization along climate and stand productivity gradients in black spruce forests of interior Alaska, Can. J. Forest Res., 35, 2118–2129, 2005.

Lathrop, R. G., Aber, J. D., and Bognar, J. A.: Spatial variability of digital soil maps and its impact on regional ecosystem modeling, Ecol. Model., 82, 1–10, 1995.

Liu, S., Post, W. M., Wei, Y., and Cook, R. B.: NACP: MsTMIP Unified North American Soil Map. Data set, available at: http://daac.ornl.gov, Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA, in press, 2012.

Mann, L. K.: Changes in soil carbon storage after cultivation, Soil Sci., 142, 279–288, 1986.

Mcguire, A. D., Joyce, L. A., Kichlighter, D. W., Melillo, J. M., Esser, G., and Vorosmarty, C. J.: Productivity response of climax temperate forests to elevated temperature and carbon dioxide: a North American comparison between two global models, Climatic Change, 24, 287–310, 1993.

Michaelson, G. J., Ping, C. L., and Kimble, J. M.: Carbon storage and distribution in tundra soils of Arctic Alaska, USA, Arctic Alpine Res., 28, 414–424, 1996.

Miller, R. O. and Kissel, D. E.: Comparison of soil pH methods on soils of North America, Soil Sci. Soc. Am. J., 74, 310–316, 2010.

Noll, C. J., Dellapenna, T. M., Gillkinson, A., and Davis, R. W.: A high-resolution geophysical investigation of sediment distribution controlled by catchment size and tides in a multi-basin turbid outwash fjord: Simpson Bay, Prince William Sound, Alaska, Geo-Mar. Lett., 29, 1–16, 2009.

Oades, J. M.: The retention of organic matter in soils, Biogeochemistry, 5, 33–70, 1988.

Oechel W. C. and Billings, W. D.: Effects of global change on the Carbon balance of Arctic plants and ecosystems, in: Arctic Ecosystems in a Changing Climate, Academic Press, California, USA,, 139–168, 1992.

O'Neil, K., Kasischke, P. E. S., and Richter, D. D.: Seasonal and decadal patterns of soil carbon uptake and emission along an age sequence of burned black spruce stands in interior Alaska, J. Geophys. Res., 108, 8155–8169, doi:10.1029/2001JD000443, 2003.

Paul, E. A.: Dynamics of soil organic matter, Plant Soil, 76, 275–285, 1984.

Ping, C. L., Michaelson, G. J., and Kimble, J. M.: Carbon storage along a latitudinal transect in Alaska, Nutr. Cycl. Agroecosys., 49, 235–242, 1997.

Ping, C. L., Michaelson, G. J., Jorgenson, M. T., Kimble, J. M., Epstein, H., Romanovsky, V. E., and Walker, D. V.: High stocks of soil organic carbon in the North American arctic region, Nature Geosci., 1, 615–619, 2008.

Post, W. M., Emanuel, W. R., Zinke, P. J., and Stangenberger, A. G.: Soil carbon pools and world life zones, Nature, 298, 156–159, doi:10.1038/298156a0, 1982.

Soil Landscapes of Canada Working Group: Soil Landscapes of Canada version 3.2. Agriculture and Agri-Food Canada (digital map and database at 1 : 1 million scale), 2010.

Quideau, S. A., Chadwick, O. A., Trumbore, S. E., Johnson-Maynard, J. L., Graham, R. C., and Anderson, M. A.: Vegetation control on soil organic matter dynamics, Org. Geochem., 32, 247–252, 2001a.

Quideau, S. A., Chadwick, O. A., Beinesi, A., Graham, R. C., and Anderson, M. A.: A direct link between forest vegetation type and soil organic matter composition, Geoderma, 104, 41–60, 2001b.

Raich, J. W. and Schlesinger, W. H.: The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate, Tellus, 44, 81–99, 1992.

Sala, O. E., Parton, W. J., Joyce, L. A., and Lauenroth, W. K.: Primary production of the central grassland region of the United States, Ecology, 69, 40–45, 1988.

Saxton, K. E., Rawls, W. J., Romberger, J. S., and Papendick, R. I.: Estimating generalized soil-water characteristics from texture, Soil Sci. Soc. Am. J., 50, 1031–1036, 1986.

Simanton, J. R., Renard, K. G., Christiansen, C. M., and Jane, L. J.: Spatial distribution of surface rock fragments along catenas in Semiarid Arizona and Nevada, USA, Catena, 23, 29–42, 1994.

Soil Survey Staff: Natural Resources Conservation Service, United States Department of Agriculture, US General Soil Map (STATSGO2), available at: http://soildatamart.nrcs.usda.gov, last access: August 2011.

Sombroek, W. G., Nachtergaele, F. O., and Hebel A.: Amounts, dynamics and sequestrations of carbon in tropical and subtropical soils, Ambio, 22, 417–426, 1993.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochem. Cy., 23, GB2023, doi:10.1029/2008GB003327, 2009.

Vasek, F. C.: Creosote bush: long-lived clones in the Mojave Desert, Am. J. Bot., 67, 246–255, 1980.

Wang, X. and Melesse, A. M.: Effects of STATSGO and SSURGO as inputs on SWAT model's snowmelt simulation, J. Am. Water Resour. Assoc., 42, 1217–1236, 2006.

Wofsy, S. C. and Harris, R. C.: The North American Carbon Program (NACP), Report of the NACP Committee of the US interagency Carbon Cycle Science Program, US Global Change Research Program, Washington DC, 2002.

Young, D. R. and Nobel, P. S.: Predictions of soil-water potentials in the North-Western Sonoran Desert, J. Ecol., 74, 143–154, 1986.

Table 1. Soil depth, source code, and attributes of top soil layer (0–30 cm) and sub soil layer (30–100 cm).

Soil Attribute	Abbreviation	Units
Maximum Soil Depth	Soil Depth	cm
Source Code	Source	na
Topsoil Sand Fraction	t_{sand}	% weight
Topsoil Silt Fraction	t_{silt}	% weight
Topsoil Clay Fraction	t_{clay}	% weight
Topsoil Gravel Fraction	t_{gravel}	% volume
Topsoil Organic Carbon	t_{oc}	% weight
Topsoil pH (H_2O)	t_{ph}	$-\log(H^+)$
Topsoil Bulk Density	t_{bd}	$\mathrm{g\,cm^{-3}}$
Subsoil Sand Fraction	s_{sand}	% weight
Subsoil Silt Fraction	s_{silt}	% weight
Subsoil Clay Fraction	s_{clay}	% weight
Subsoil Gravel Fraction	s_{gravel}	% volume
Subsoil Organic Carbon	s_{oc}	% weight
Subsoil pH (H_2O)	s_{ph}	$-\log(H^+)$
Subsoil Bulk Density	s_{bd}	$\mathrm{g\,cm^{-3}}$

Table 2. Soil organic carbon concentration (OC) and bulk density (BD) of field studies in Alaska.

Location	Land Cover	Depths(cm)	BD ($g\,cm^{-3}$)	OC (%)	Reference
Barrow	Moist acidic tundra	0–30	0.96	12.4	Michaelson et al. (1996)
		30–100	0.97	8.9	
Barrow	Wet acidic tundra	0–30	0.58	11.72	
		30–100	1.11	9.08	
Nello Pingo	Moist acidic tundra	0–30	0.41	31.82	
		30–100	0.40	7.46	
Betty Pingo	Moist nonacidic tundra	0–30	0.78	11.27	
		30–100	0.38	12.40	
Betty Pingo	Wet nonacidic tundra	0–30	0.60	21.3	
		30–100	0.38	11.7	
AK Pipline Mile 24	Wet nonacidic tundra	0–30	0.39	13.60	
		30–100	0.89	3.17	
Sagwon Hills	Moist nonacidic tundra	0–30	0.59	7.95	
		30–100	1.00	4.38	
Toolik Lake	Moist acidic tundra	0–30	0.47	11.65	
		30–100	0.52	5.63	
Toolik Lake	Wet acidic fen	0–30	0.47	10.8	
		30–100	0.30	8.9	
Imnaviat Creek	Wet acidic tundra	0–30	0.09	41.81	
		30–100	0.26	34.08	
Imnaviat Creek	Moist acidic tundra	0–30	0.62	11.6	
		30–100	0.83	8.8	
Sag River	Riparian shrubland	0–30	1.15	1.00	
		30–100	0.98	0.80	
Sag River	Wet acidic tundra	0–30	1.03	4.84	
		30–100	0.92	2.42	
Happy Valley	Moist acidic tundra	0–30	1.00	4.75	
		30–100	0.71	8.84	
Atigun River Gorge	Alpine	0–30	1.5	2.5	
		30–100	2.03	0.9	
Betty Pingo	Marsh	0–30	0.62	21.6	Ping et al. (1997)
		30–100	1.53	3.68	
Happy Valley	Tussock tundra	0–30	0.62	21.64	
		30–100	1.53	3.68	
Toolik Lake	Shrub tundra	0–30	0.86	9.07	
		30–100	1.47	2.70	
Coldfoot, Alaska	Boreal Forest	0–30	0.25	48.59	
		30–100	1.39	5.80	
Smith Lake, Alaska	Bog	0–30	1.08	16.48	
		30–100	1.13	10.3	
Delta Junction	Forest	0–30	0.66	3.82	
		30–100	1.23	1.13	
Nancy	Boreal forest	0–30	0.77	7.64	
		30–100	0.95	0.99	
Pt. MacKenzi	Bog	0–30	0.15	52.92	
		30–100	0.37	39.00	
Sukoi	Coastal forest	0–30	0.56	14.51	
		30–100	0.93	3.04	
Tanana Valley	Black spruce	Organic horizon	0.11	34.5	O'Neil et al. (2003)

Table 3. The SOCM for major vegetation types in the top 0–30 cm and the 0–100 cm soil profile in North America derived from the NCSCD-modified UNASM soil carbon map and HWSD 1.1.

Soil Layer	Needle Trees (Pg)	Broad Leaf Trees (Pg)	Mixed Trees (Pg)	Shrubs (Pg)	Grasses (Pg)	Crops (Pg)
NCSCD-modified UNASM Soil Organic Carbon Map						
0–30 cm	28.21	6.14	1.30	21.72	1.73	5.72
0–100 cm	70.80	11.84	3.27	49.26	4.64	13.05
HWSD						
0–30 cm	32.89	9.12	1.59	13.70	1.93	5.27
0–100 cm	63.73	13.69	2.86	26.29	4.06	10.16

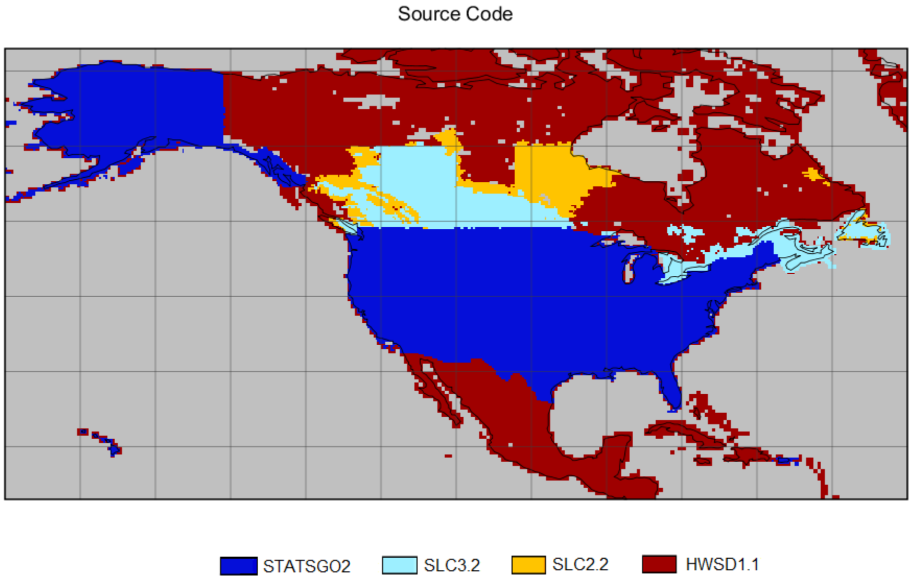

Fig. 1. The spatial distribution of data sources for the UNASM.

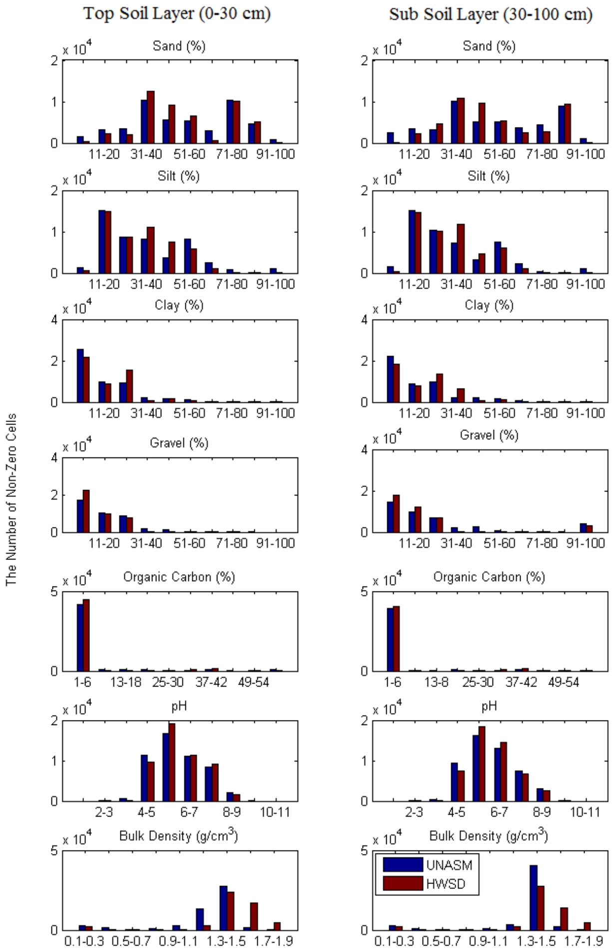

Fig. 2. The histogram and the mean of soil properties of the top soil layer (0–30 cm) and sub soil layer (30–100 cm) in the UNASM and the subset of the HWSD 1.1.

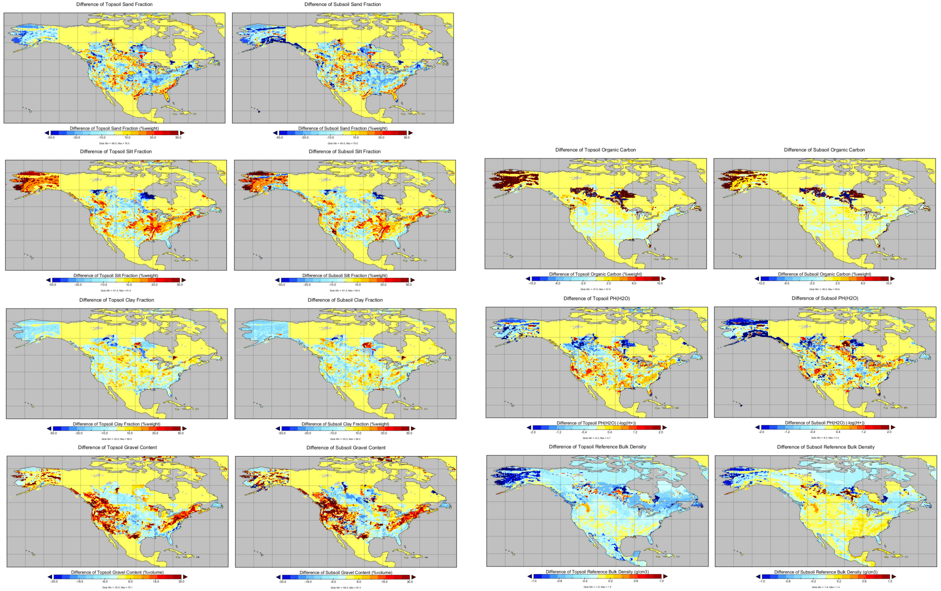

Fig. 3. The difference map between the UNASM and the subset of the HWSD 1.1 for each soil property. The top soil ranges from 0 to 30 cm and the sub soil ranges from 30 to 100 cm.

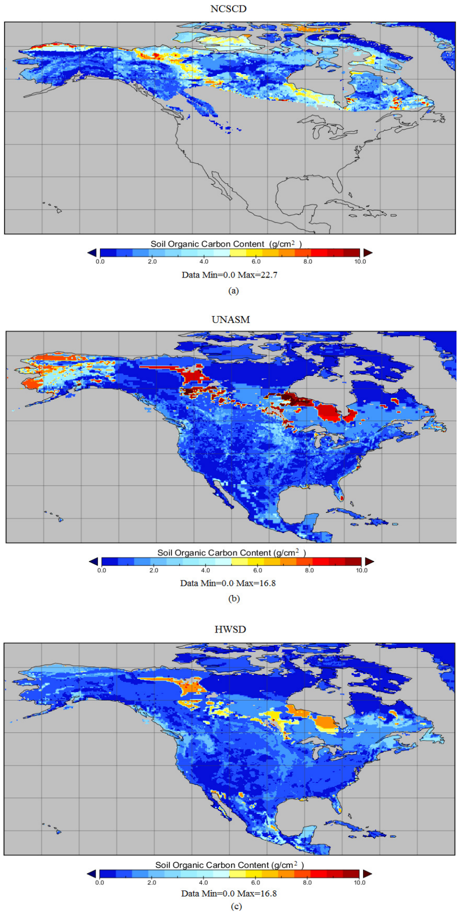

Fig. 4. SOCC in the top 100 cm soil profile derived from **(a)** the NCSCD, **(b)** the UNASM and **(c)** the HWSD 1.1.

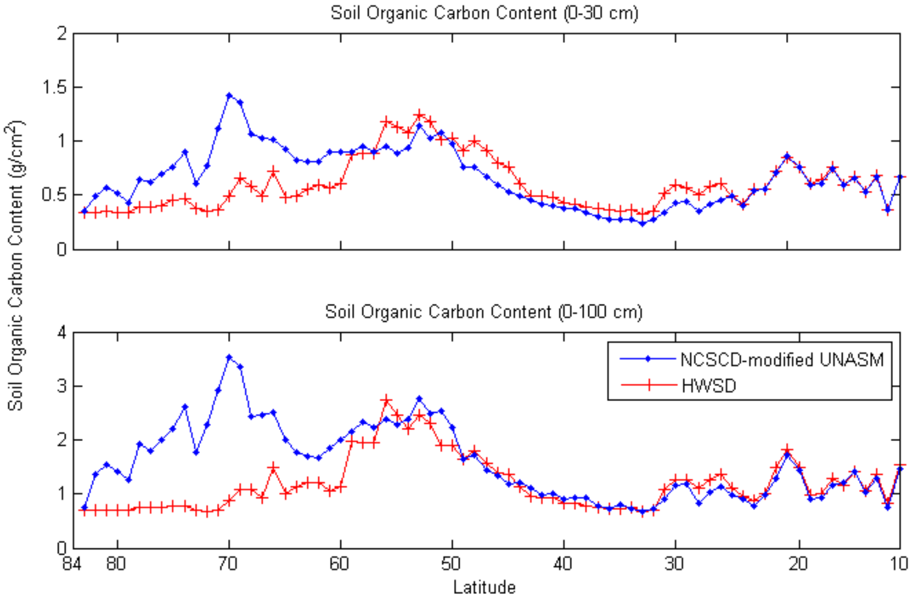

Fig. 5. The latitudinal mean SOCC in **(a)** the 0–30 cm and **(b)** the 0–100 cm soil profile.

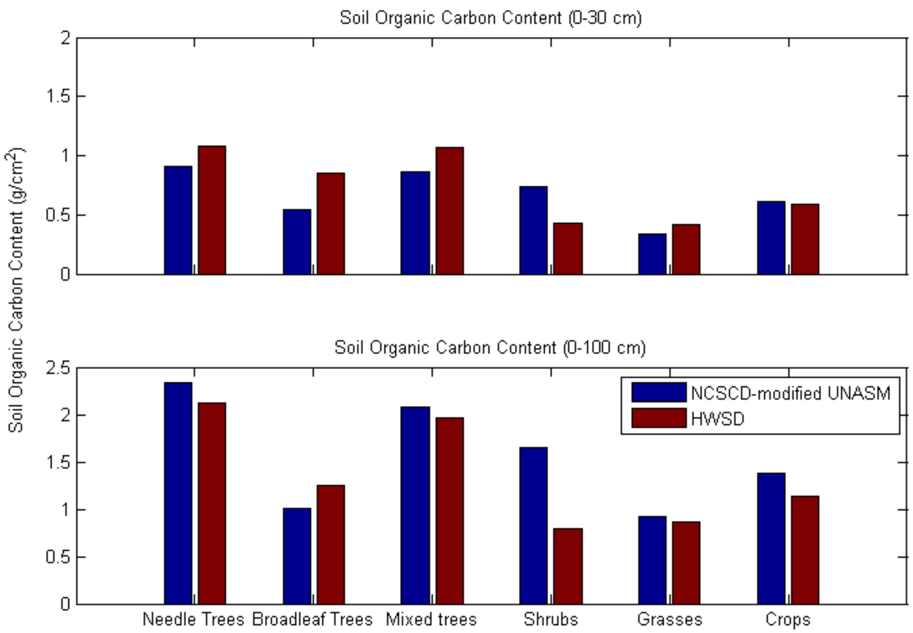

Fig. 6. The mean SOCC for major vegetation types in **(a)** the 0–30 cm and **(b)** the 0–100 cm soil profile.

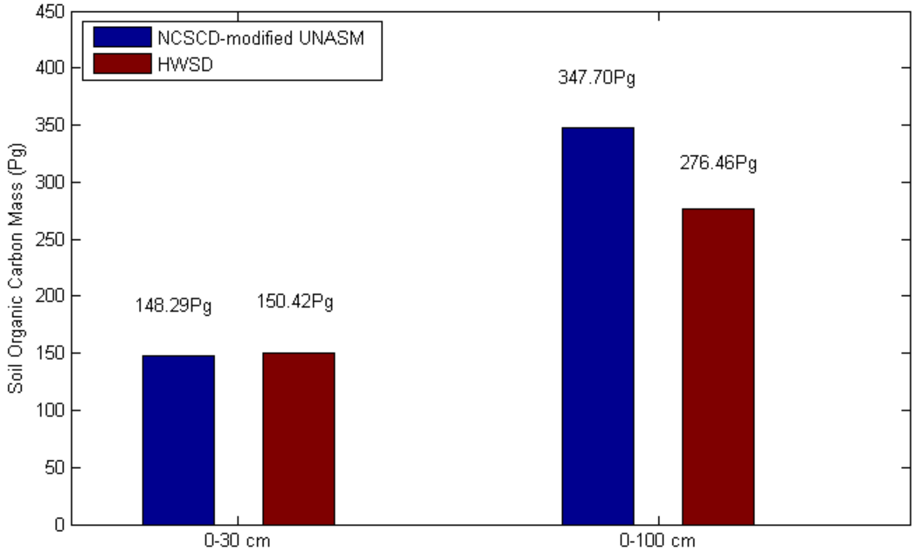

Fig. 7. The SOCM of the top 0–30 cm and the 0–100 cm soil profile in North America derived from the NCSCD-modified UNASM soil organic carbon map and HWSD 1.1.