Geoderma 334 (2019) 124–133

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Baseline map of soil organic carbon in Tibet and its uncertainty in the 1980s

Y. Zhou[a], R. Webster[b], R.A. Viscarra Rossel[c], Z. Shi[a,d,*], S. Chen[e]

[a] College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China
[b] Rothamsted Research, Harpenden AL5 2JQ, UK
[c] CSIRO, PO Box 1666, Canberra, ACT 2601, Australia
[d] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China
[e] INRA, Unité Infosol, Orléans 45075, France

ARTICLE INFO

Handling Editor: A.B. McBratney

Keywords:
Soil organic carbon
Digital soil mapping
Tibetan Plateau
Soil carbon stock
Climate change

ABSTRACT

Much of the carbon (C) stored in the soil of the high Qinghai–Tibet Plateau could be lost as a result of global warming. To provide a baseline against which to assess the loss we have made a new map at 90-m resolution from sample data of 1148 soil profiles augmented by information on climate, vegetation, physiography and digital elevation. We used the program Cubist, which works as a form of regression tree, to predict the concentration at the nodes of the 90-m grid. The uncertainty of the predictions was computed by bootstrapping 50 times at each node. Soil type, evapotranspiration (ET), precipitation, radiation and vegetation type contributed most to the variation in C at the coarse scale; temperature, net primary productivity, normalized difference vegetation index (NDVI), ET and elevation contributed most at finer scales. We mapped the predicted concentration of C and converted the predictions to stocks of C for the main kinds of land: 1.93 Pg for the alpine steppe, 1.57 Pg for the meadow, 0.66 Pg in the coniferous forest, 0.63 Pg in the broadleaf forest, 1.06 Pg under shrub, < 0.4 Pg for each of the alpine desert and cropland. We estimate the uppermost 30 cm of soil to contain 6.81 Pg of C with 95% (3.80 to 10.27 Pg). This estimate differs substantially from the two previous coarser estimates based on global modelling which far exceed our 95% upper confidence limit. Our new estimate can now serve as a base against which to judge any change of soil C as a response to global warming.

1. Introduction

Soil contains more carbon than the rest of the terrestrial biosphere and plays a vital role in the global carbon cycle. We now realize that the soil's organic carbon in particular is increasingly important in the behaviour of ecosystems, both natural and agricultural. If the soil were to sequester more carbon it would help to mitigate the effects of emissions of the greenhouse gases to the atmosphere from fossil fuel, and simultaneously it should improve the quality and productivity of the soil to provide food (Nadeu et al., 2015). Alternatively, loss of carbon from the soil would exacerbate the effects. Nearly one quarter of the earth's land is mountain where loss of carbon from the soil could have serious consequences for global climate warming and ecological functioning (Kapos et al., 2000; Yang et al., 2008). Carbon stored in the soil of world's mountain grasslands and shrub lands is estimated to be between 60.5 and 82.8 Pg (Ward et al., 2014); this is one of the most important reservoirs of carbon.

Many investigators have studied the characteristics and controls of organic matter in the soil of high ecosystems and monitored changes in them. Nevertheless, the difficulties of studying at such high altitudes and the heterogeneity of the landscapes mean that our knowledge of the amount of carbon stored and its patterns of distribution remains very uncertain (Liu et al., 2012).

The Qinghai–Tibet Plateau, familiarly known as 'the roof of the world', with an area of 2 500 000 km^2 and an average altitude of 4500 m, is the largest ecosystem at this height on earth. Much of it is underlain by permafrost in which stored C is inactive. Of general concern is that with global warming some or all of the permafrost will melt, making the carbon available to microbial attack and the release of CO_2 into the atmosphere (Ding et al., 2016). The topography of the Plateau is far from flat; rather it is complex. In southeastern Tibet, for example, the land falls more than 500 m within 1 km in valleys. Such dramatic change in height is accompanied by substantial variation in the soil.

Despite the complexity of the land form, the Plateau is an ideal region for studying the effects of climate on the soil's organic carbon. Unlike lower lands, it has scarcely been disturbed by human activity. Nevertheless, the difficulties of access and logistics for sampling on the Plateau's mean that there have been few attempts to estimate and map

* Corresponding author.
E-mail address: shizhou@zju.edu.cn (Z. Shi).

https://doi.org/10.1016/j.geoderma.2018.07.037
Received 5 December 2017; Received in revised form 22 July 2018; Accepted 27 July 2018

the soil's organic C content there (Dörfer et al., 2013, Ma et al., 2016; Yang et al., 2016) and very few for the whole of the Plateau. Those studies have focused on specific vegetation or soil types such as grasslands and permafrost. Further, sampling has been sparse compared with those studies in other mountain area (Ballabio, 2009; Hoffmann et al., 2014). For example, Yang et al. (2016) predicted the organic in the soil of approximately 30 000 km^2 from a sample of only 99 points, and Yang et al. (2008) estimated the stock of C in Tibetan grasslands, which cover 60% of the total plateau (approximately 1 200 000 km^2) from data of 405 soil profiles. Most of our understanding on the spatial distribution and temporal dynamics of organic C in the soil is from research on individual landscapes and small regions or on single forms of land cover.

To improve our understanding of the effects of height on the distribution of the soil's organic C across the Plateau we need maps at fine resolution of both carbon content and its uncertainty.

There are several global soil maps, such as the harmonized world soil database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), SoilGrids1 km (Hengl et al., 2014) and SoilGrids250 m (Hengl et al., 2017) and currently the GlobalSoilMap (Arrouays et al., 2014) with at a 3 arc-second resolution. We, however, are concerned specifically with the Qinghai–Tibet Plateau, and the aim of the research we report here was to map at 90-m resolution of the concentration of organic C in the soil of the Plateau. This would provide a baseline against which to assess future change. We pursued our aim by collating the most comprehensive currently available data on the the soil's content of organic C from the Plateau and building a soil–landscape model with multiple environmental co-variables by data-mining.

2. The study region

Our study region is the Tibet Autonomous Region (Tibet for short hereafter),78 ° 25′ N and 99° 06′ E and 26° 50′ and 36° 53′ N, which is the main component of the Qinghai–Tibet Plateau, covering more than 120 000 km^2 (Fig. 1a). A large proportion of the land (86%) exceeds 4000 m above sea level, and somewhat more than half (53%) lies above 5000 m. However, because of the logistic difficulties mentioned above we have concentrated our effort on one part of the Plateau, namely the Sygera Mountain (Fig. 1a).

The Sygera Mountain is one of the most accessible parts of Tibet, and we have been able to study its soil and environment in some detail. It hosts several types of vegetation that occur elsewhere on the Plateau. These include agricultural crops in the fertile valleys at the foot on the mountain and broad-leaved forests at mid-altitudes(mainly below 2500 m). Above them in sequence of increasing altitude are coniferous forests, shrubs and finally alpine meadows above 4500 m. The Mountain's climate is somewhat wetter than elsewhere with annual precipitation of approximately 676 mm. Its mean monthly temperatures range from 0.5 to 15.8 °C. We regard it as typical sub-humid alpine caused by the South Asian monsoon which approaches through the valley of the Brahmaputra River. There is, however, a trend from warm and humid in the south east to colder and drier in the north west.

3. Methods

3.1. Soil depth functions to derive estimates of organic C in the 0–30 cm layer

We wanted to predict the concentration of organic C in the uppermost 30 cm of the soil. The data from the National Soil Survey of China are recorded by soil horizons at various intervals in the profiles. To predict from such data we used the equal-area smoothing spline developed by Bishop et al. (1999) and Malone et al. (2009) to describe the way the concentration of C varies down the profile. This is obtained as follows.

We denote the depths of the lower boundaries of the layers in any given soil profile by $x_i, i = 0,1,2,…,n$, such that $x_0 < x_1 < x_2,…, < x_n$. We associate with each layer i a corresponding value of the soil property y of interest as y_i. We then model y as

$$y_i = \overline{f_i} + \varepsilon_i \tag{1}$$

where $\overline{f_i}$ is the mean value of y at depth between x_{i-1} and x_i, and ε_i is a measurement error with a mean of 0 and a variance of σ^2. We denote $f(x)$ as the spline function of the soil property at depth x, which we find by minimizing

$$f(x) = \frac{1}{n}\sum_{n=1}^{n}(y_i - \overline{f_i})^2 + \lambda \int_{x_0}^{x_n} \{f'(x)\}^2 dx \tag{2}$$

where the first term on the right-hand side represents the fit of the spline to the data and the second term expresses the roughness of the function $f(x)$. The parameter λ controls the trade-off between the fit and the roughness of the spline. Bishop et al. (1999) and Malone et al.

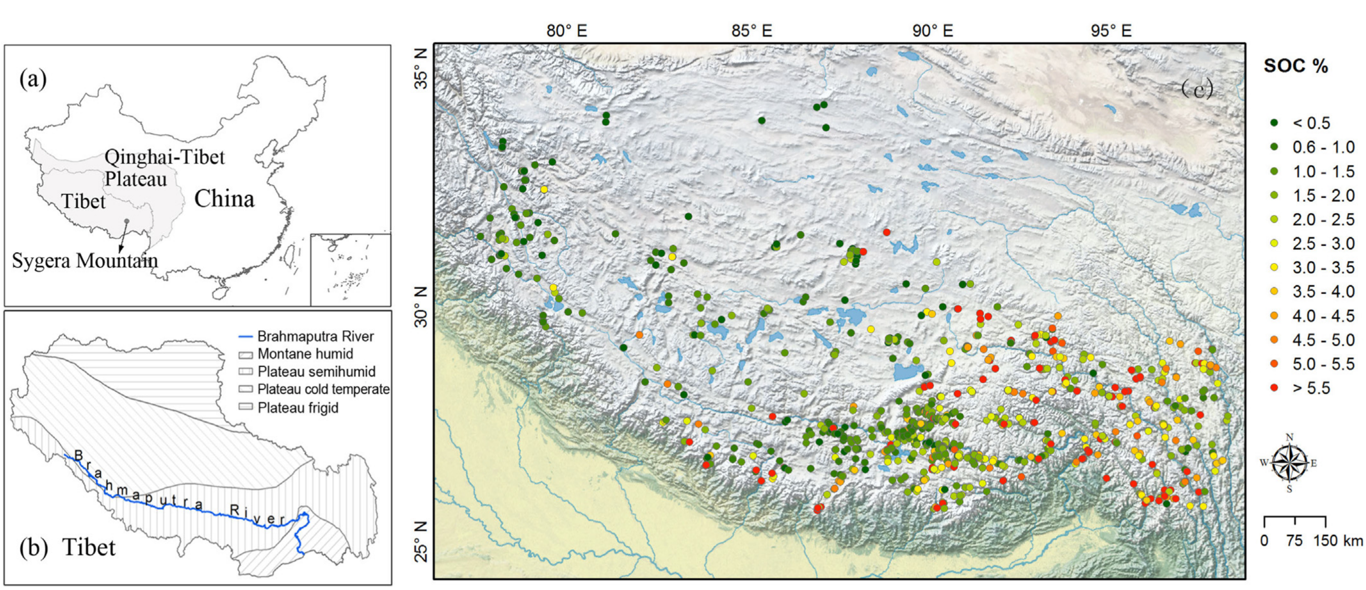

Fig. 1. Spatial distribution of soil samples used for modelling and validation. (a) Presents the location of Tibet, Sygera Mountain, Qinghai-Tibet Plateau and China. (b) Presents the climate zone in Tibet and the Brahmaputra River, and (c) Presents the soil samples we collected in Tibet.