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Soil Organic Carbon Stock in Hindu Kush Himalayn's Grasslands

Jianguo Qi, Xinze Li

Shandong Agricultural University, Tai'an, Shandong, 271018, China

Abstract: *The knowledge of carbon (C) stock and its dynamics is crucial for understanding the role of grassland ecosystems in Hindu Kush Himalayan (HKH) terrestrial C cycle. To date, a comprehensive assessment on C balance in HKH's grasslands is still lacking. By reviewing published literature, this study aims to evaluate soil organic carbon (SOC) stock in HKH's grasslands. Our results are summarized as follows: (1) SOC density varied greatly between 1.6 and 11.7 kg C m^{-2}. (2) The magnitude of SOC in Grassland ecosystems in different countries of HKH region differed greatly. (3) Spatial patterns of grassland SOC were closely correlated with climate and topography. Human activities, such as livestock grazing and fencing could also affect soil C dynamics in HKH's grasslands.*

Keywords: *HKH, Grassland, SOC density, SOC change, Topography*

1. Introduction

Grassland is one of the most widely distributed ecosystems on Earth and plays an important role in the global terrestrial carbon cycle (Scurlock and Olson, 2002). About 34% of the global terrestrial C is stored in grasslands and a significant (89%) amount of the C sequestered by the grassland vegetation is stored in the soil (White et al., 2000). Grasslands in HKH are an important component of the world's grassland ecosystems. Natural grasslands in HKH cover an area of 2.29×10^6 km^2 (Joshi et al., 2013), accounting for ~60% of the HKH area. Due to the large C stock, grasslands may play a key role in HKH's terrestrial C cycle (Piao et al., 2009). Thus, our knowledge of C stock and its dynamics in grassland ecosystems not only helps our understanding of the potential role of grassland ecosystems in HKH's terrestrial C cycle, but also provides a basis for sustainable use of limited grassland resources in HKH.

Among the countries in HKH region, China occupies 67.48% of grassland area, which is mainly in Tibet, Qinghai, Sichuan, Gansu and Yunnan provinces. The other 32.52% of grassland is distributed in Pakistan, Afghanistan, India, Nepal, Bhutan, Myanmar and Bangladesh (Joshi et al., 2013). During the past several decades, a number of studies on SOC cycling, particularly on SOC stock and its changes, have been conducted for China's grasslands at different scales. However, there is still lack of systematic and overall research on SOC storage in other countries of HKH, and these studies have usually examined SOC stock and its dynamics for specific grassland types (e.g.,temperate or alpine grasslands). Consequently, regional or national scale assessments of the SOC balanceare still lacking.

To investigate SOC stock in grasslands of HKH, we review previous research to provide a comprehensive regional or national assessment of SOC stocks and the potential factors that influence SOC dynamics in HKH's grasslands.

2. Materials and methods

Using Google Scholar searching engine, we obtained a total of 553 articles on "grassland" or "rangeland" in "HKH/Himalaya/Himalayan", "India/Indian", "Nepal/Nepalese", "Pakistan/Pakistani", "Burma/Myanmar/Burmese", "Bangladesh/bangladeshi", "Bhutan/Bhutanese", "Afghanistan/Afghan", of which only 19 articles were related to SOC in HKH region. In the Tibetan plateau of the HKH region, there are 52 articles directly related to the measurement of SOC. The SOC sampling positions from 71 papers were extracted and shown in Figure 1. The basemap is MODIS land use classification product MCD12Q1, using the Land_cover_type1 standard for land cover classification and grassland classification. By sorting out the literature, the carbon storage data of each country in the HKH region are determined.

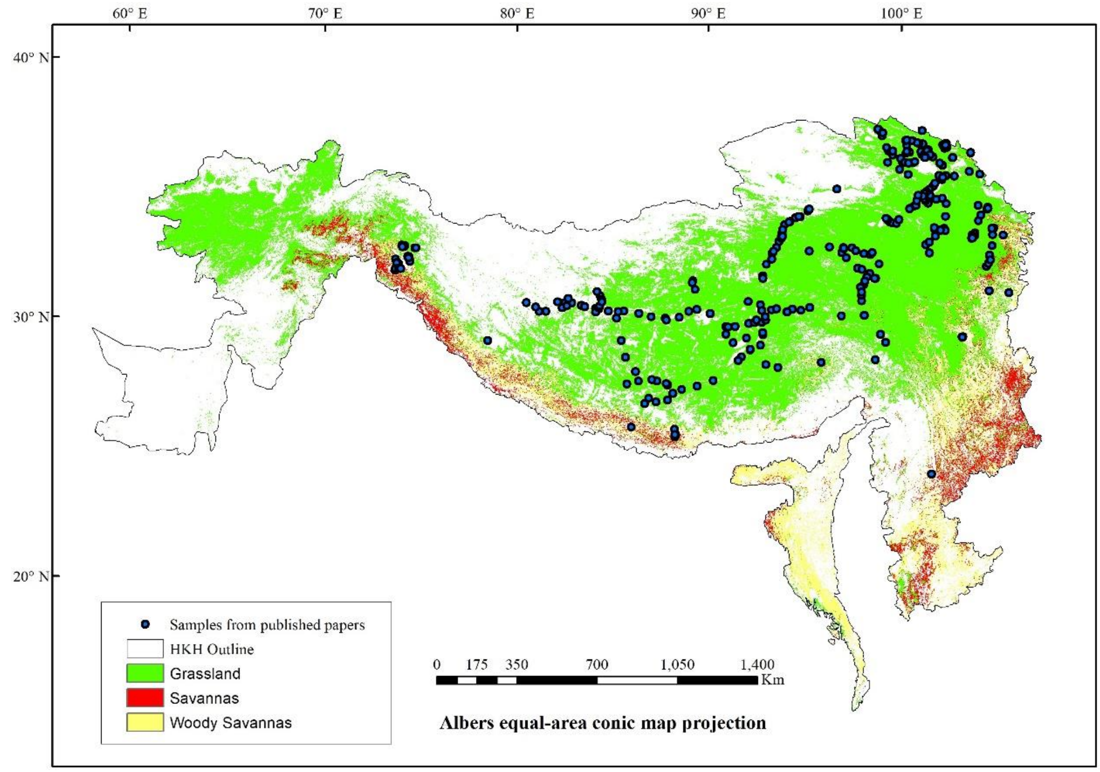

Figure 1: The distribution of soil sampling plots from published papers

3. Soil organic carbon stock

Among the eight countries in the HKH region, China was the first country to systematically conduct soil carbon storage studies, followed by India and Nepal. Although Afghanistan and Pakistan respectively occupies 12.74% and 8.22% of the grassland area of HKH, their grassland carbon storage research is relatively poor, and only part of the literature describes vegetation C (Ahmad et al., 2006). In Myanmar, Bhutan and Bangladesh, there is no literature on grassland SOC.

In China, using data obtained from the First National Soil Survey and published literature, Fang et al. (1996) provided the first estimate for China's soil C stock. Since then, a number of studies have been conducted to evaluate SOC stocks in grassland ecosystems, especially at Tibet plateau. However, large differences exist among previous studies (Table 1). For example, Fang et al. (1996) estimated soil C density in the Tibetan grasslands at 21.4 kg C m^{-2}. Their estimate was much higher than other reports, since rock fragments were not deducted and because of insufficient soil profiles from the First National Soil Survey. Likewise, Wang et al. (2002) documented a similar estimate (20.9 kg C m^{-2}) using the same data obtained from the First National Soil Survey plus field measurements surveyed in the eastern part of the Tibetan Plateau. However, based on data from MODIS vegetation index and 405 soil profiles sampled from 135 sites across the Tibetan Plateau, Yang et al. (2008) reported soil C stock in the top 100 cm to be about 7.4 Pg C,with an average soil C density of 6.5 kg C m^{-2}. These results were much lower than those reported by Fang et al. (1996) and Wang et al. (2002).

Studies on grassland carbon stocks in India are mainly concentrated in Orissa state and northwest regions. In view of the fact that Orissa is not in the HKH region, it mainly analyzes grassland SOC in northwestern India. Among them, Jangra et al. (2010) measured the SOC bulk density and carbon content of the northwestern sodic grassland soil from surface to 100 cm and SOC density was between 1.66 to 2.47 kg C m^{-2}. In order to better determine the total amount of carbon in the Uttarkhand, through statistical Uttarkhand grassland area and measured carbon density of 30 cm soil thickness, Chupa and Sharma (2013) estimated the grassland soil carbon storage at 26.77 million ton. Different grassland types have different SOC density, Thokchom and Yadava (2016) reported the SOC density of Imperata grassland is 5.5-5.7 kg C m^{-2}. Javaid (2019) conducted a comprehensive measurement of the carbon storage in the mountain grassland soil of northwestern Kashmir Himalaya. Its measuring depth was 50cm and SOC density ranged between 2.885 and 9.476 Kg C m^{-2}, with mean value of 5.452 Kg C m^{-2}, which was stored as 30.63, 22.98, 21.06, 14.89, and 10.41%, respectively at five depths (0-10; 10-20; 20-30; 30-40 and 40-

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50 cm). Comparing these studies in northwestern India, grassland SOC density in uttarakhand is significantly higher, while SOC density measured by Jangra is relatively low.

Grassland soil carbon research in Nepal is mainly concentrated in central and eastern part. Ghimire et al. (2016) measured the soil organic carbon storage of degraded grassland 0-10cm as 2.63 Kg C m^{-2}. Limbu et al. (2013) measured the soil carbon density at different depth of 0-5, 5-10, and 10-15 cm, but the more appropriate method for characterizing the 0-15cm carbon density should be to accumulate the carbon density of each layer rather than to average it. Although the area of measurement is not very large, the density of soil organic carbon varies greatly between Jaljale (9.4 kg C m^{-2}) and Gorujure (4.9 kg C m^{-2}).

The reason for the difference in SOC density measured in the field depends largely on the grassland type, grassland depth, altitude, soil type, soil pH, and soil fertility (Wiesmeier et al., 2019). However, from the perspective of regional carbon stock estimates, the large differences among these estimates may be due to the following four aspects: First, different data sources or approaches were used. Regional estimates were ground-based measurements at large spatial scales or by biogeochemical model. Although the national or regional soil survey provided the most comprehensive soil information, few soil profiles were sampled from core areas of China's grasslands, such as the Tibetan Plateau and Xinjiang regions (Yang et al., 2007; Yang et al., 2008; Xie, 2004). In contrast, Yang et al. (2007, 2008) obtained a much larger number of soil profiles across the Tibetan Plateau, potentially resulting in a more accurate estimate. Nevertheless, some uncertainties still exist due to insufficient soil profiles in certain regions, such as the northwestern part of the Tibetan Plateau (Yang et al., 2008).

Second, a lack of data on bulk density and rock fragments may produce different estimates. It is well known that a number of soil profiles in HKH do not contain information about bulk density (Wu et al., 2003; Wang, 2000; Yang et al., 2007; Yang et al., 2008; Xie, 2004). Previous studies used average soil bulk density by soil category (Chen et al., 2003) or the relationship between bulk density and soil C concentration (Xie et al., 2007) to estimate bulk density. The different treatment of bulk density data could lead to potential differences in soil C estimates. Alternatively, most estimates used average values of rock fragment as a substitute. However, a few studies did not deduct rock fragments, resulting in larger estimates. According to Wu et al. (2003), ignoring rock fragment will overestimate soil C stock by 10%, but in grasslands, a larger error could occur due to the larger proportion of rock fragments in grassland soils.

Table 1: Comparison of soil C density and C stock among different studies

Region/Site	Area (10^4 ha)	Depth (cm)	SOCD# (kg C m^{-2})	SOCS# (Pg C)	Data resource and approach	Reference
China Tibetan Plateau	165.0	68.5	21.4	35.4	China's First National Soil Survey and data from literature	(Fang et al., 1996)
China Tibetan Plateau	160.3	65	20.9	33.5	Field measurements and China's Second National Soil Survey	(Wang et al., 2002)
China Tibetan Plateau	147.7	20	6.6	9.7	China's Second National Soil Survey, Century model	(Zhang et al.,2007)
China Tibetan Plateau	112.8	100	6.5*	7.4	Field measurements and satellite dataset (EVI)	(Yang et al., 2008)
China Tibetan Plateau	112.8	30	3.89*	4.39	Field measurements and satellite dataset (NDVI)	(Yang et al., 2009)
India Kurukshetra - Sporobolus marginatus		100	1.66		Field measurements	(Jangra et al., 2010)
India Kurukshetra - desmostachya bipinnata		100	2.47		Field measurements	(Jangra et al., 2010)
India Uttarakhand	22.89	30	11.698	0.0267	Field measurements	(Gupta & Sharma, 2013)
India Kurukshetra- desmostachya bipinnata		100	2.879		Field measurements	(Jangra et al., 2015)
Inida Manipur		30	5.6*		Field measurements	(Thokchom & Yadava, 2016)
Northwestern Kashmir Himalaya		50	5.452*		Field measurements	(Dad, 2019)
Nepal Jikhu Khola Catchment		10	2.63		Field measurements	(Ghimire et al., 2013)
Nepal Jaljale		15	9.4		Field measurements	(Limbu et al., 2013)
Nepal Gorujure		15	4.9		Field measurements	(Limbu et al., 2013)
Nepal Milke		15	5.4		Field measurements	(Limbu et al., 2013)

(* indicates the average SOC in the sampling area; SOCD# indicates soil organic carbon density; SOCS# indicates soil organic carbon stock)

Third, different scaling-up approaches were used in various studies. Previous studies usually calculated SOC stock by averaging soil C density by soil categories or grassland types. This approach could be constrained by a limited number of soil profiles and large soil heterogeneity. Accordingly, spatial interpolation or satellite-based approaches have been developed to scale up site-level observations to regional-scale estimates, which could reduce the uncertainty induced by soil heterogeneity (Yang et al., 2010; Yang et al., 2008).

Finally, grassland area may be inaccurate. The current grassland area is mostly obtained by accumulating grassland pixel data in land cover products. However, this method ignores the relief of the terrain in the pixels, making the calculated grass area smaller than the real grass area. Chen and Arrouays (2017) analyzed the Harmonized World Soil Database (HWSD) data and found that when the terrain slope in the pixel is less than 20°, the ratio of the true area to the pixel area is within 1.1; Once the slope is greater than 30°, the real area will be significantly larger than the pixel area, resulting in a serious underestimation of SOC stock. In addition, the current classification algorithms are mostly based on existing grassland classification standards, and the classification of grassland types is relatively coarse. For example, the optimal classification of grassland by MCD12Q1 data is grassland, savanna, and woody savanna, but the measurement of vegetation carbon density mostly corresponds to the grassland types such as alpine grasslands and alpine meadows. Grassland classification level mismatch will also affect the estimation of carbon storage.

4. Effects of environmental factors on SOC

SOC stock in China's grasslands is closely correlated with environmental factors. For instance, Yang et al. (2008) reported that SOC stock in Tibetan alpine grasslands was largely determined by precipitation and soil texture. Specifically, SOC density in Tibetan alpine grasslands increased with both precipitation and clay content but decreased with sand content. Temperature played a minor role in shaping soil C density in these grasslands. In total, these environmental factors explained 72.1% of the variations in soil C density. However, by integrating the grassland SOC literature in China, Xu et al. (2018) found that climate influenced the spatial patterns of vegetation C and SOC density via different approaches, vegetation C was mainly positively influenced by mean annual precipitation, whereas SOC was negatively dependent on mean annual temperature.

In addition to precipitation and tempeture, Topography is a important factor to influence the distribution of SOC (Wiesmeier et al., 2019). Current researches often use three terrain factors—aspect, slope, and elevation to characterize complex terrain. The aspect of the slope affects the intensity of the incident solar radiation and the duration of sunlight, which in turn affects its ecological processes and create a microclimate that is different with regional climate conditions (Zhang et al, 2015). These microclimate conditions have a certain effect on the vegetation communities and species distribution (AStröm et al, 2008). In the Mountains of southwestern China, Pu et al. (2008) found that the carbon storage on the windward slope (east slope) was more than leeward slope (western slope). In general, the sun-aspect can get more solar radiation and generate higher temperature and water loss, which is not conducive to the growth of plants and fixation of SOC. There is a clear positive correlation between SOC and elevation (Peng et al., 2013). From Javaid (2019) field measured result, we can find same conclusion. An increase in elevation will result in increased precipitation and low temperature. This will increase vegetation carbon input while inhibiting soil carbon decomposition, which will be beneficial to SOC accumulation (Wiesmeier et al., 2019). Slope affects water flow paths, water accumulation, and discharge and therefore contribute significantly to erosional processes (Wiesmeier et al., 2019). Generally, in areas where vegetation water use is limited, there will be more soil erosion on the slope, which is not conducive to SOC accumulation. However, in areas with sufficient moisture, slopes will reduce disturbance from human and livestock, which is beneficial to SOC accumulation (Li et al., 2018).

5. Conclusions

Based on a comprehensive review of current literature, this study examined SOC stock and its changes in HKH's grasslands and analyzed the potential effects of natural factors and human activities on C dynamics. Our analyses showed that SOC density ranged from 1.6 to 11.7 kg C m^{-2}. Due to the limitation of the number of field sampling points and the lack of different types of grassland area, SOC stock in HKH grassland has not been estimatedand. Our analyses also indicated that SOC stock was increased in China's Tibetan Plateau and parts of northwestern India from 1980s to 2010s. Both spatial and temporal dynamics in soil C stock was largely determined by climate and topography. Human activities, such as livestock grazing and fencing, also exerted strong effects on ecosystem C dynamics in China's grasslands.

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