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A comprehensive framework for evaluating the impact of land use change and management on soil organic carbon stocks in global drylands

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Drylands play major roles in the terrestrial carbon cycle and mitigation of climate change. Understanding the dynamics of soil organic carbon (SOC) stocks under land use change and management is essential for achieving soil C sequestration through land-based solutions for drylands. In this paper, we briefly reviewed the literature to evaluate the impact of land use change and management on dryland SOC stocks. While the site-level field measurements of SOC stocks under different types of land use change and land management are remarkable, we found that the impact is hardly quantified at the regional level using selected soil datasets or process models and may be due to insufficient data quality, representativeness and information availability, which are among the major challenges of upscaling from field measurements to estimating regional SOC stocks. Therefore, we proposed a comprehensive framework following the IPCC inventory approach to improve future studies, which underlines the needs of data collection from multiple sources, meta-analysis for calculating SOC stock change factors, and matching land and soil datasets.

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Introduction

Soil organic carbon (SOC) is the largest carbon (C) stock in most terrestrial ecosystems. It was estimated that 1463−2011 Pg (1 Pg = 10^{15} g, namely, 1 billion tons) of organic C is stored in soil to 1 m depth globally [1]. The change in global SOC stock can have a significant impact on the atmospheric carbon dioxide (CO_2) concentration and thus affect global climate change. In addition to climate conditions and soil properties, land use change and related management practices are major forces driving the dynamics of SOC stocks. On the one hand, deforestation, cultivation, and other land use changes may cause a large quantity of SOC to breakdown and release CO_2 into the atmosphere and contribute to global warming. On the other hand, afforestation and reforestation, farmland management, restoration of degraded lands, and other land management practices can increase the accumulation of aboveground vegetation C and SOC stocks, thereby playing the ‘carbon sequestration’ role in slowing the rise in atmospheric CO_2 concentrations [2]. Therefore, evaluating SOC stocks affected by land use change and management is critical for developing land-based climate solutions [3].

Drylands, broadly defined as land areas where the aridity index (i.e., the ratio of mean annual precipitation to mean annual potential evapotranspiration) is less than 0.65, represent major ecosystems in tropical and temperate regions among all continents [4]. The limited biomass productivity, soil water deficit and other unique soil physicochemical properties have contributed to the relatively low SOC content in drylands [5], where soil degradation and desertification prevail. Soil organic C losses and C emissions from degraded drylands can be mitigated by adopting restoration measures that improve soil quality, increase SOC content, and enhance biomass productivity [6]. Recent studies have shown that dryland ecosystems dominate the global terrestrial C sequestration trend and largely contribute to the interannual variability in atmospheric CO_2 concentrations over the past decades [7–9]. Several studies have also suggested that dryland ecosystems have strong C sequestration potential [10–12]. However, great uncertainty remains regarding the broad-scale dynamics of SOC stocks in drylands in the case of comparing estimates with different methods [13]. While the environmental controls on the variation in SOC stocks have been examined across diverse dryland ecosystems [14], there has been a lack of an adequate evaluation of the land use change and management impact on dryland SOC stocks, which poses a challenge to achieving soil C sequestration through sustainable management and utilization of land resources in global drylands.

In this review, we summarize the research progress made in evaluating the impact of land use change and management on SOC stocks of global drylands, with a focus on the methods used for evaluating the regional SOC stocks. Based on the review results, we propose a comprehensive framework and suggestions for improving the evaluation of dryland SOC stocks under land use change and management in future studies, with the aim of providing support to decision-makers and other stakeholders in developing mitigation strategies within the dryland context.

Overall trend of land use change and management in global drylands

According to the most recent studies, global drylands cover a total area of 66.7 million km^2, which is approximately 45.4% of the Earth's land area [15,16•]. At the global scale, the situation of land uses in drylands is not fully understood. It was estimated that 11%, or 7.6 million km^2, of the global dryland area is used as cropland and 30%, or 20.2 million km^2, is used as pasture. That is, drylands cover 50% of global croplands and 74% of pastures [17••]. By contrast, using remotely sensed data from various sources, researchers have gained a better understanding of land use and its changes in major dryland regions worldwide. The literature shows that the reduction in forests and other natural vegetation and the expansion of croplands and grazed grasslands, driven mainly by human migration and economic development, have occurred over the past decades in developing dryland regions, such as the oasis regions in North Africa [18], the Sahel region [19], the Brazilian Caatinga [20] and Central Chile in South America [21], and Central Asia [22,23]. The literature shows notably different trends of land use across more developed regions characterized by long-standing, intensive dryland farming and grazing management, such as the adoption of conservation tillage practices in the north-central US [24], the formation of a more natural forest landscape owing to the reduction in agricultural activities in the Mediterranean region of Europe [25], afforestation in Israel's semiarid regions [26], and the development of agroforestry systems in southwest Australia [27]. Thus, it is obvious that the change in land use and management in drylands is a dynamic process over the long term, which is closely associated with socioeconomic development. These human-driven land use changes and management practices have significantly altered the structure and functioning of dryland ecosystems [28], and their impact on dryland soil resources and SOC stocks is of concern for researchers worldwide [17••,29].

Field measurements of SOC stocks under land use change and management

A number of observational and experimental studies have been conducted in typical dryland ecosystems to measure SOC stocks by content (%) or density (g C m^{-2} or t C ha^{-1}) under various land uses and management practices. Considering that the SOC stock varies as a function of the texture, bulk density, organic matter content, and microbiological activity in the soil, the measurement of SOC is often based on a composite sampling method or mixing soil samples from different soil profiles to obtain one average sample [30] for a specific land use or management practice at the study site. The differences in SOC content or density since the land use change or management practices occurred could be used to determine the impact on SOC stocks at the site. The existing evidence suggests that the SOC stocks of drylands may significantly decrease due to the conversion of native forests to farmlands and/or grazing lands [31] and livestock grazing and/or shrub removal (root ploughing) [32], while the stocks may increase in the case of afforestation of degraded cropland [33,34] and sandy land [35,36], grazing exclusion for grassland restoration [37], and conversion of grassland to organic agriculture [38], which occurs at a rate that varies with local climatic conditions, soil types, and so on [39]. In dryland agricultural systems, it is notable that conservation farming practices, such as crop rotation, cover cropping, straw mulching, reduced tillage and/or no-tillage benefit from maintenance or increasing of SOC stocks [40,41•]. Conversion to irrigation can also increase C inputs and thus SOC stocks in dryland cultivated fields [42]. In general, site-level field measurements provide an important basis for our understanding of the mechanisms of land use change and management impacts on SOC stocks in drylands.

Evaluating the regional SOC stocks under land use change and management

The evaluation of regional SOC stocks requires a sampling stratification or devising a sampling strategy to upscale from site measurements [30], which represents a key methodological issue in terrestrial C cycle studies [43]. Along with the increase in the number of field measurements, the soil datasets could be compiled with spatially explicit information on soil properties, including SOC content. These datasets are increasingly used to evaluate the regional SOC stocks in drylands. For example, the Harmonized World Soil Database (HWSD) and the Digital Soil Map of the World (DSMW) have been used to assess and map the SOC stock in the Sudanese woodland savannah and the Arab countries, respectively [44,45]. Recently, using an updated harmonized dataset of derived soil properties for the world at a nominal resolution of 30 by 30 arc sec (WISE30sec), the mass of organic C stored in dryland soils was estimated to be 470 ± 7 Pg to 1 m (646 ± 9 Pg to 2 m), or 32% of the global SOC stock [17••]. This estimate is greater than the 431 Pg, or 27% of the global stock previously reported [46], due to differences in both the dryland extent and the soil geo-databases used for estimation. Soil datasets can be easily used in combination with land use and land cover maps to evaluate regional SOC stocks, but the accuracy of the evaluation results depends greatly on the volume and distribution of soil samples. In addition, they are rarely used to predict present or future SOC dynamics due to the lack of information about SOC turnover.

In recent years, SOC dynamic modelling based on the processes of organic C accumulation and decomposition has advanced significantly. Some of the process-based models were used to simulate the dynamics of SOC stocks in drylands, revealing the different contributions to the SOC stocks under climate change and/or land use change and management. For example, the Arid Ecosystem Model (AEM) has been used to analyse spatiotemporal changes and climate controls of carbon stocks in the drylands of China [47] and over Central Asia [48] since the 1980s. The AEM was also integrated with an empirical C bookkeeping model to investigate the coupled and isolated effects of climate change and arable land conversions on the regional vegetation C and SOC stocks in a typical watershed of northwest China [49•]. The Agricultural Production Systems sIMulator (APSIM) was combined with surrogate modelling to predict SOC dynamics from 2009 to 2070 for Australian dryland cropping soils under farmers' common management practices and future climate conditions [50••]. The C model CQESTR, pronounced 'sequester', was used to simulate SOC dynamics and predict SOC responses to management, crop rotation and climate change in the Northern Great Plains Region of the US [51,52]. The Century model was also calibrated and validated at two sites in semiarid NE Brazil to simulate the C dynamics of Caatinga dry forest before and after deforestation [53]. A few years earlier, the Rothamsted Carbon (RothC) model was modified and tested from cropping sequence experiments to improve SOC dynamics prediction in semiarid regions [54]. The SOC models provide a useful tool to simulate historical changes and predict the trends of SOC stocks, especially for agroecosystems in drylands. However, their application at the regional scale is largely limited by computational requirements, data availability, and model uncertainties [50••].

Researchers have noticed the differences in SOC stocks when estimated with different methods (Table 1). For example, the SOC stock to a 1 m depth in Central Asia was estimated to be 30.82 ± 18.61 Pg with the field measurements of 284 soil samples, which was higher than the 27.15 Pg value obtained with the AEM [55]. Estimates of the SOC stocks in Mexico also indicate that the estimates with field measurements were 15% higher on average than those with the HWSD or the Dynamic Global Vegetation Models (DGVMs) [13]. It appears that the existing process-based models and soil databases underestimate the SOC turnover rate or densities under certain conditions in drylands.

Given the uncertainties and discrepancies that may exist among single-site or independent studies, it is necessary to compile and compare the results of these studies through quantitative synthesis techniques, such as meta-analysis. Since the 2010s, the number of meta-analyses on the effect of land use change and management on SOC stocks has been increasing steadily worldwide [56,57]. A few studies have been conducted to address the impact of Mediterranean woody crops [58], afforestation [59•], and various land use changes [60] on SOC stocks and have suggested promising options to increase the C stored in dryland soils. More evidence could be derived from meta-analyses based on the dataset compiled from published studies for policy-makers to make decisions on soil C sequestration in drylands.

A comprehensive framework for evaluating the land use change and management impact on SOC stocks in global drylands

As shown in Table 1, current studies may still provide insufficient quantitative evaluation of the regional SOC stocks in drylands. In particular, the integrated effect of land use change and management on regional SOC stocks is sparsely quantified regardless of whether select soil datasets or process models are used. This finding indicates that there are major challenges in upscaling from a number of field measurements to estimations of broad-scale patterns and dynamics of SOC stocks, which may be due to insufficient soil data quality (such as only bulk density and no C content, shallow depth of sampling, and so on), representativeness (in terms of soil types and climate variability), and little information regarding land use history and management practices [61]. Previously, the Intergovernmental Panel on Climate Change (IPCC) developed a bottom-up inventory approach for estimating changes in SOC stocks due to land use and management over time. The change in SOC stocks is calculated from a reference SOC stock under native vegetation using three dimensionless factors representing land use or land use change type, management regime and input of organic matter. Default values for these factors and the reference SOC stock are provided in the guidelines for inventories [62••]. The method is relatively simple and can be applied in regions with fewer resources or information to account for SOC stocks.

Here, we propose a comprehensive framework for evaluating SOC stocks under land use change and management in global drylands (Figure 1). Based on the IPCC inventory approach, this framework consists of three major components: the spatial analysis of land use change and management, the estimation of reference SOC stocks (to 30 cm depth as suggested by the IPCC [62••]) and stock change factors, and the inventory of SOC stocks prepared by matching the former two components. This framework underlines the need for several elements to be taken into consideration. First, both land and soil data need to be collected from multiple sources to increase

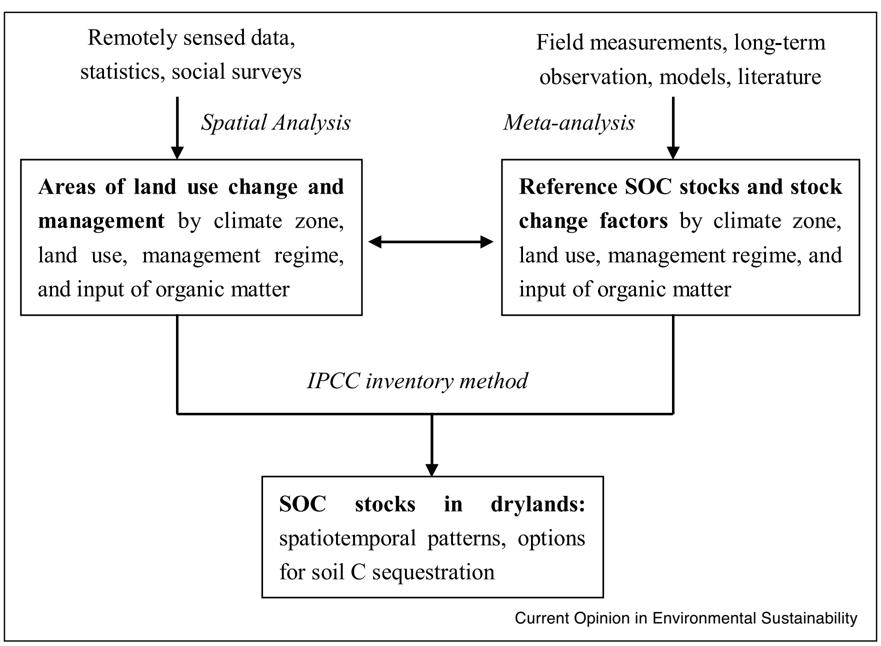
Table 1

Evaluation of regional SOC stocks in drylands

Period	Land type or region	Area/ 10^6 ha	Soil depth/cm	SOC		Change in SOC		Methods	Ref.
				Stock/Pg	Density/ kg m^{-2}	Stock/ Tg a^{-1}	Density/ kg m^{-2} a^{-1}		
	Global	14 900	30 100 200	750 ± 15 1425 ± 21 2047 ± 39				WISE30sec	[17••]
	Sudanese woodland savannah	80.4	100		5.45 ± 1.81			HWSD	[44]
	Arable lands in Arab countries	1160	100	50.5	7.8 ± 6.9			DSMW	[45]
1980–2014	Arid region of China	~250				0.14–0.17		AEM	[47]
1980–2014	Central Asia			45.2 ± 0.01				AEM	[48]
1979–2014	Cropland expansion in Manas River watershed	0.337		0.012		0.338		AEM + bookkeeping	[49•]
2009–2070	Australian rainfed crop areas		30				−0.18	APSIM + surrogate models	[50••]
2014	Central Asia	468	100	30.82 ± 18.61	6.59 ± 3.98			Field measurements	[55]
1979–2011				27.15	5.81 ± 4.09	3.44	0.735	AEM	
2000–2005	Mexico	195.7	20	14.16 ± 3.86	4.7−12.1			Average	[13]
				13.86 13.49 15.13				HWSD DGVMs Field measurements	

A negative sign of changes indicates a source to the atmosphere, and a positive sign indicates a sink. 1 Pg = 10^{15} g, namely, 1 billion tons; 1Tg = 10^{12} g, namely, 1 million tons.

Figure 1



A comprehensive framework for evaluating SOC stocks under land use change and management in drylands.

data size or improve data quality in dryland regions, especially where little land use history or no complete soil survey exists. Second, instead of using the IPCC default values, the SOC stock change factors can be estimated from meta-analyses of soil data collected from multiple sources (e.g., soil surveys, field experiments, and models). In particular, experimentation and long-term field experiments are important sources of data on the SOC turnover rate, a key parameter to improve the accuracy of estimation. The SOC models can also provide stimulated values at sites without field measurements in the region. Third, the land areas and SOC stock change factors in certain climate zones (e.g., arid, semiarid, and dry subhumid areas) need to be estimated and matched by land use, management practices, and input of organic matter for estimating the inventory of SOC stocks. Finally, the inventory and spatiotemporal analysis of SOC stocks can help identify options for soil C sequestration in drylands. This comprehensive framework can be tested through case studies in typical dryland regions with plentiful research efforts, such as in arid northwest China.

Conclusions

Drylands have experienced notably different trends of land use change and management in different regions worldwide. To date, a number of observational and experimental studies have been conducted in typical dryland ecosystems to measure SOC stocks and help us understand the mechanisms of land use change and management impact on SOC stocks in drylands. At the regional level, several methods have also been used to evaluate the SOC stocks in drylands. However, the integrated effect of land use change and management on regional SOC stocks is sparsely quantified regardless of whether selected soil datasets or process models are used, which may be due to the challenges of insufficient data quality, representativeness and information availability for upscaling from field measurements. Following the IPCC inventory approach, a comprehensive framework that underlines the needs of data collection from multiple sources, meta-analysis for calculating SOC stock change factors, matching the land and soil datasets by climate zones, land use, management practices, and input of organic matter is thus proposed for future studies to improve the evaluation of SOC stocks under land use change and management in drylands.

Conflict of interest statement

Nothing declared.

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