Recent Trends in Soil Degradation Research in Drylands: Soil Organic Carbon, Temperature and Water as Affected by Land Use and Climate Change

Aki HOSHINO

Division of Appropriate Technology and Sciences for Sustainable Development,
Graduate School of Life and Environmental Sciences, University of Tsukuba
1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8577 Japan
e-mail: hoshino.aki.gn@u.tsukuba.ac.jp

Abstract

This review focuses on the effect of soil degradation due to land use on climatic variables (soil temperature and water), the effect of climatic variables on soil organic matter (SOM) decomposition rate in drylands, and the effects of soil degradation and concurrent climate change on soil organic carbon (SOC) accumulation. There is contradictory evidence about the effect of soil degradation on soil temperature and water, and the effect of soil temperature and water on SOC accumulation. From a general viewpoint, soil degradation and drought increase soil temperature and decrease soil water, both of which result in decreased SOC accumulation. On the other hand, from the viewpoint of recent results from drylands, water deficits decrease the decomposition rate of SOM, consequently causing increased SOC accumulation in drylands. However, decreases in aboveground net primary production (NPP) due to land degradation may accelerate wind erosion and fertile soil loss. Therefore, the extent of soil degradation and concurrent climate change would be deeply related to the above-ground NPP in drylands.

Key words: climate change, cultivation, decomposition rate, overgrazing, soil degradation, wind erosion

1. Introduction

Drylands occupied 41% of the Earth's land area, and they were home to more than two billion people – a third of the human population – in the year 2000 (Millennium Ecosystem Assessment, 2005). A previous study reported that about 23% of the world's drylands are affected by soil degradation (Zika & Erb, 2009). That study also reported that the semi-arid zone shows the largest areas of degraded land, with 4.8 million km^2, followed by the arid zone (4.5 million km^2) and the dry sub-humid zone (2.5 million km^2). Especially in the semi-arid grasslands of Northeast Asia, soil degradation with decreasing soil organic carbon (SOC) due to overgrazing and improper cropping has become a serious problem in recent decades (Pankova, 1994; Su *et al.*, 2004; Zhao *et al.*, 2005; Steffens *et al.*, 2008). Crop cultivation generally decreases SOC due to accelerated mineralization, leaching, translocation and erosion (Lal, 2002; Su *et al.*, 2004), and reduces aggregate stability as a result of organic matter loss and the breakdown that occurs due to tillage (Li & Shao, 2006). Overgrazing can decrease SOC because of the decrease in litter supply and the increase in soil respiration (Wang & Ripley, 1997; Cao *et al.*, 2004). It can also weaken aggregate stability through organic matter depletion and trampling (Manzano & Návar, 2000). The reduction in SOC leads to weak aggregate stability (Tisdall & Oades, 1982) and a decrease in soil water, known as holding capacity (Li *et al.*, 2007), which together, largely account for wind erosion. In many arid and semi-arid regions, wind erosion can be substantial and the dominant form of soil erosion (Breshears *et al.*, 2003; Field *et al.*, 2009). Dryland in Northeast Asia is highly susceptible to wind erosion in early spring which is characterized by sparse vegetation and a strong northwesterly wind (Wang and Xue, 2010). Cropland (Liu *et al.*, 2003; Zhao *et al.*, 2006) and overgrazed grassland (Natsagdorj *et al.*, 2003; Li *et al.*, 2004) where vegetation cover is sparse in spring, in particular, can be easily eroded by wind (*e.g.* Fig. 1). The extent of soil erosion was mainly dependent on the soil water content of, and the wind speed over, degraded bare ground. Moreover, soil water content has a negative correlation with soil temperature (*e.g.*, increases in soil temperature decreases soil water content). Therefore, climatic conditions and soil conditions are deeply related to wind erosion.

Furthermore, in terms of global climate change, the soil C pool has become a subject of widespread interest.

Fig. 1 Typical grassland (front side) and abandoned cropland (far side) in spring time in Hustai National Park, Mongolia. While the land surface is covered with the sprouts of perennial species (in green) in typical grassland, bare ground (in light brown) is formed in abandoned cropland. (Photo by A. Hoshino taken in May 2008)

The world's soil constitutes the third largest global C pool: 1,500 Pg of SOC and 950 Pg of soil inorganic carbon to a 1-m depth, which is especially important in soils of dry regions (Lal, 2004b; 2007). Therefore, clarifying the effect of climate change on SOC turnover rate is a critical issue for sustainable land management in drylands (MEA, 2005). In fact, increasing air temperatures in winter and increasing drought frequency have been observed recently in Northeast Asia (Yatagai & Yasunari, 1994; Dai *et al.*, 1998; Lotsch *et al.*, 2005). Several climate models suggest that future global warming may reduce soil water over large areas of semi-arid grassland in North America and Asia (Manabe & Wetherald, 1986). The sensitivity of the soil organic matter (SOM) decomposition rate to temperature and soil water should be clarified in drylands. In addition, studying the effects of concurrent soil degradation on temperature and soil water conditions in drylands, which are characterized by low, highly variable precipitation, is critical for predicting the SOC turnover rate in drylands. This review, therefore, focuses on the effects of soil degradation due to land use on temperature and water content, the effects of climatic variables on SOM decomposition rate in drylands, and the effect of soil degradation and concurrent climate change on SOC accumulation.

2. Effects of Soil Degradation Due to Grazing and Cultivation on Soil Water and Temperature in Drylands

2.1 Grazing

Generally, grazing reduces soil water in the root zone at a depth of 0–15 cm (Lecain *et al.*, 2000; Donkor *et al.*, 2006) in the short term (Donkor *et al.*, 2006). Simulating grazing by clipping did not consistently increase soil temperature nor soil water over a one-year period. Similarly, Risch *et al.* (2007) reported that soil temperature and soil water trends observed during the growing season were not affected by grazing. They suggest that the probable reason for not finding such grazing-related differences in soil temperature and water could be related to compensatory growth of the vegetation, resulting in the same amount of aboveground net primary production (NPP) in non-grazed and grazed areas (Risch & Frank, 2006). This result provides a critical insight into soil degradation due to overgrazing in rangeland ecosystems because a rangeland is resistant to intensive grazing due to the long history of grazing. In such rangeland, standing biomass is not decreased by grazing immediately. For example, grass species, which have high compensatory growth ability, begin to grow when grazing intensity increases (Van Staalduinen, 2007). Therefore, soil temperature and water would not change so much due to increased grazing intensity. However, if heavy grazing decrease the standing biomass and litter - and changes the soil surface to bare ground accompanied by structural soil destruction by trampling - soil temperature will increase and soil water content will decrease (Wan & Luo, 2003; Donkor *et al.*, 2006). The effects of grazing on soil temperature and water depends on the resistance of the ecosystem and grazing intensity.

2.2 Cultivation

Generally, cultivation increases soil temperature (Alvarez *et al.*, 2001; Bono *et al.*, 2008) and decreases soil water content (Li & Shao, 2006; Hoshino *et al.*, 2009, Fig. 2) due to tillage practices in drylands. Tillage practice increase macro pore, which reduces the upward flow

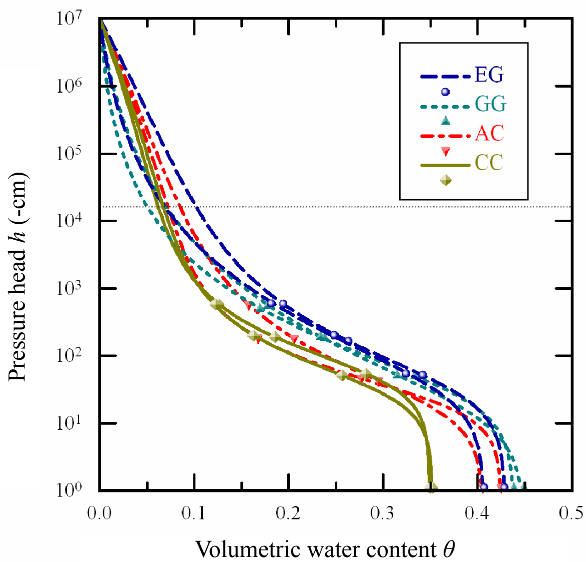

Fig. 2 Soil water-retention curves for the soil samples from the four sites: pressure head as a function of the volumetric moisture content. EG: grassland with grazing exclusion, GG: grazed grassland, AC: abandoned cropland, and CC: continuously cultivated cropland. The horizontal line represents the wilting point (h = 15,000 cm). Every site has the repetition; the two curves with the same style represent the water-retention properties from the same site. Symbols indicate observation points, and each curve was calculated using observation values. At low suction values, the water content at a given suction was smaller at CC than at the other sites (Hoshino *et al.*, 2009).

from deeper layer, consequently thermal conductivity would decrease. In terms of SOC conservation when faced with erosion and climate change, there are studies on the comparison of no-tillage cropping with conventional tillage practices. In earlier studies, the initial period coincided with higher soil temperatures in the conventional tillage treatment (Alvarez *et al.*, 2001; Bono *et al.*, 2008). Soil temperature was similar between no-tillage and conventional tillage over a 3-year period (Bono *et al.*, 2008). That is, although there may be some difference in the effect of cultivation methods on soil temperature and water content, cultivation generally increases soil temperature and decreases soil water content.

3. Effect of Soil Water and Temperature on Contents of the Soil Organic Matter and Organic Matter Decomposition Rate in Drylands

SOC stocks result from the balance between inputs and decomposition of SOM. Soil temperature and water measurements are critical to a better understanding of the effects of future climate change on SOM and its decomposition rate (Sims & Nielsen, 1986; Homann *et al.*, 1995; Alvarez & Lavado, 1998; Leirós *et al.*, 1999; Bellamy *et al.*, 2005). Increasing temperature lead to increases in the decomposition rate of SOM and decreases in SOC accumulation (Jurgensen *et al.*, 2006; Ineson *et al.*, 1988; Hopkins *et al.*, 1990; Drewnik, 2006; Withington & Sanford, 2007). Generally, the surface SOC concentration is positively correlated with soil water (Burke *et al.*, 1989; Grigal & Ohmann, 1992; Hontoria *et al.*, 1999; Ganuza & Almendros, 2003; Dai & Huang, 2006). In addition, severe depletion of the SOC pool in degraded soil conditions may be exacerbated by projected global warming (Lal, 2004a).

In drylands, such as grasslands, however, negative correlation between soil temperature and the decomposition rate of SOM (Homann & Grigal, 1996; Risch *et al.*, 2007) and positive correlation between soil water content and the decomposition rate of SOM (Risch *et al.*, 2007, Fig. 3) have been reported. As soil water is a primary limiting factor in the grassland ecosystem, changes in soil water are probably more important to the alteration of SOM decomposition rates than temperature (Epstein *et al.*, 2002; Risch *et al.*, 2007). Previous studies have also suggested that increasing temperature would not lead to a reduction in SOC in largely water-limited drylands (Gifford, 1992; Risch *et al.*, 2007). Epstein *et al.* (2002) suggested that increases in temperature will enhance the water deficit in the region (Lauenroth *et al.*, 2004) and will lead to decreases in the aboveground NPP.

In addition, decomposed SOM consists of decomposition - labile (active) and - stable (passive) SOM pools (Parton *et al.*, 1987). Labile SOM pools mainly consist of young SOM (Parton *et al.*, 1987). On the other hand, stable SOM, being the major fraction of SOM, has a larger effect on the C sink–source relationship. However, there are contradictory assertions about the temperature

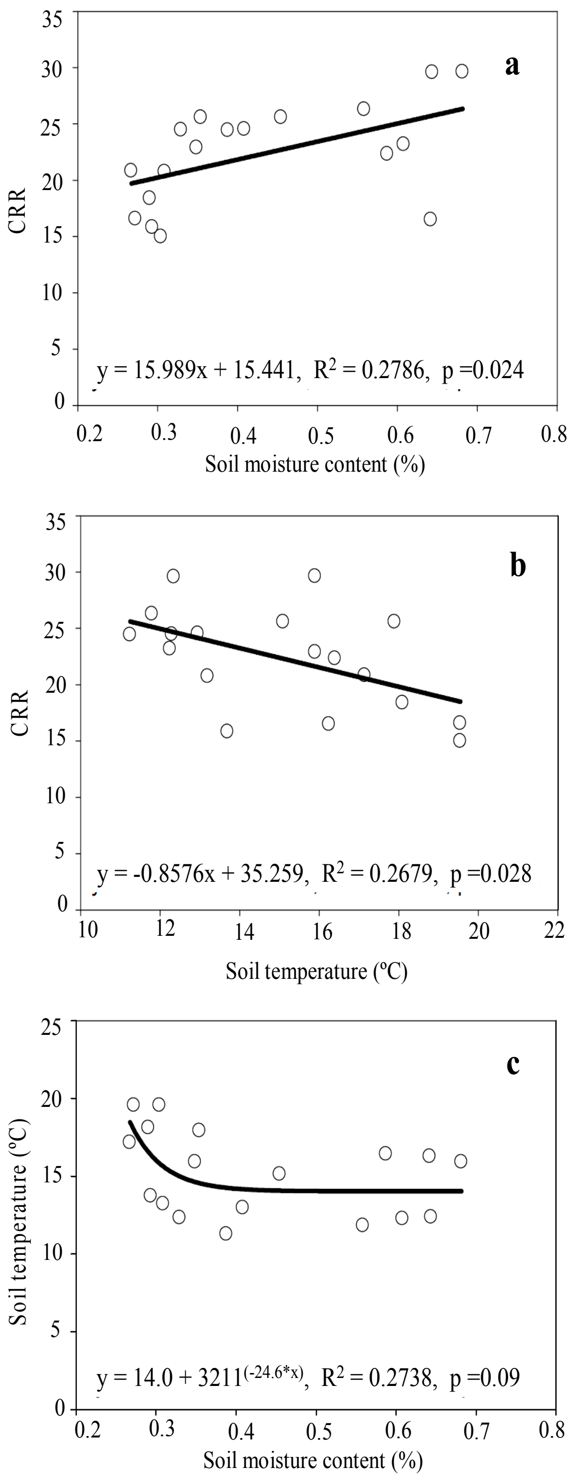

Fig. 3 Changes in CRR (= cotton rotting rate; season averages of decomposition given as rate of decomposition), soil moisture and soil temperature across the Yellowstone National Park landscape during the 2004 growing season (Risch *et al.*, 2007). a: relationship between CRR and soil moisture, b: relationship between CRR and soil temperature, c: relationship between soil moisture and soil temperature. n=18 for all three graphs. Cotton cloth decomposition rates were significantly and positively correlated with soil moisture. A negative relationship between CRR and soil temperature (b), which was weakly negatively correlated (exponential decay function) with soil moisture (c). Temperature especially affected soil moisture for dry condition, while no effect of temperature was detected for the wetter condition (c).

sensitivity of labile and stable SOM. Some sources say that the decomposition rate of stable SOM has higher or similar temperature sensitivity than that of labile SOM (Fang *et al.*, 2005; Conen *et al.*, 2006; Conant *et al.*, 2008). Other say that the decomposition rate of stable SOM is not temperature sensitive (Giardina & Ryan, 2000; Eliasson *et al.*, 2005; Karhu *et al.*, 2010). There is also insufficient study of the water sensitivity of labile and stable SOM (Yurova & Lankreijer, 2007). As mentioned, soil water is a critical factor in the decomposition rate especially in drylands; therefore, future work to clarify the soil water sensitivity of labile and stable SOM is required in order to predict the effects of climate change on the C sink-source relationship.

4. Effect of Soil Degradation Due to Land Use and Concurrent Climate Change on Soil Organic Carbon Accumulation

There is contradictory evidence about the effects of soil degradation on soil temperature and water content, and the effects of soil temperature and water content on SOC accumulation. Looking at the responses of these factors to the prediction of SOC dynamics, soil degradation due to grazing and cultivation increases soil temperature and decreases soil water content. In addition, increased soil temperature and decreased soil water content decreased SOC accumulation, and those changes are accelerated by increasing frequency of droughts in the growing season, which is regarded as one of the most serious effects of climate change in Northeast Asia (Yatagai & Yasunari, 1994; Dai *et al.*, 1998; Lotsch *et al.*, 2005).

On the other hand, from the viewpoint of recent results from drylands, grazing, which does not decrease aboveground NPP, would not affect the soil water content (Risch & Frank, 2006). In the case of drought, decreased soil water content would increase SOC accumulation (Risch *et al.*, 2007). In a water-limited ecosystem, a water deficit also decreases the decomposition rate of SOM, consequently increasing SOC accumulation. Moreover, a decrease in aboveground NPP accelerates wind erosion which causes loss of fertile soil (Ravi *et al.*, 2010).

Those recent studies strongly suggest that the extents of soil degradation and concurrent climate change would have an interactive relationship with aboveground NPP in drylands. Therefore, integrated and empirical research to clarify their interactions is urgently required as a future work (Fig. 4).

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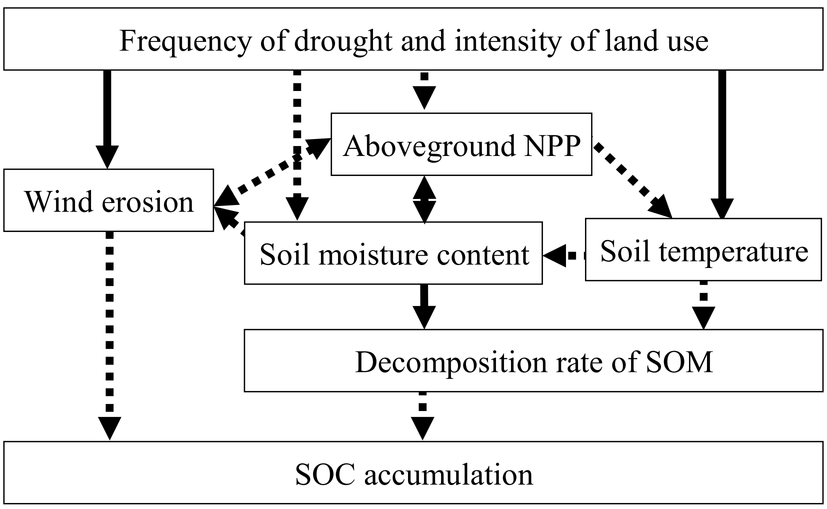

Fig. 4 Conceptual diagram showing the interrelations among climate change (frequent drought), land degradation due to land use and SOC accumulation in drylands. Solid and dot lines show a positive and negative relationship, respectively. Arrows show the direction of interrelation of each factor.

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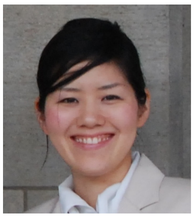

Aki HOSHINO

Aki Hoshino is a postdoctoral fellow at the Graduate School of Life and Environmental Sciences, University of Tsukuba. She received her Master degree in soil science at the University of Tsukuba, and defended her PhD. in Landscape Ecology and Planning at the University of Tokyo. She has been focusing on land degradation and recovery processes in abandoned cropland in semi-arid Mongolia from the stand point of the relationship between soil hydraulic properties and plant species composition. Her main interest is soil hydrological processes and their relationship with other factors such as plant species composition and soil chemical properties in degraded agricultural land in arid regions.

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