Response of the Plant and Soil Features to Degradation Grades in Semi-arid Grassland of the Inner Mongolia, China

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Abstract. As a result of climate change and human activities over the past century, grassland degradation has a profound impact on the carbon storage process. We aimed to research the effects of grassland degradation on plant and soil features and soil carbon emission rate. The carbon content decreased in the leaves but increased in the roots as the degradation gradient increased. The net ecosystem exchange was -8.29 µmol.m⁻².s⁻¹, -3.14 µmol.m⁻².s⁻¹ and -1.57 µmol.m⁻².s⁻¹ in LD (light degradation), MD (moderate degradation) and SD (severe degradation) grassland, respectively. The carbon emission rate (7.22, 6.56 and 4.22 µmol.m⁻².s⁻¹) decreased significantly as the degradation grade increased.

1. Introduction
Grassland vegetation is an important part of the terrestrial ecosystem. Carbon stocks account for approximately 15.2% of the total terrestrial ecosystem (Ajtay, 1979). The grassland ecosystem is widely distributed in China and covers 41% of the land area, with Inner Mongolia occupying 25% of the grassland (Ni, 2002). Grassland ecosystems have profound impacts on soil sinks and sources (Piao et al., 2009), and enhanced ability for carbon and nitrogen sequestration, thereby influencing global environmental change (Wright et al., 2004). However, 90% of grasslands (3.99 billion ha) have been degraded by climate change and human activities over the past several decades (Ren et al, 2007a). Grassland degradation is defined as the process of environmental deterioration and leads to desertification caused by overexploitation, poor management, climatic warming and drought (Zhou et al., 2005; Li et al., 2011). Grassland degradation causes altered composition of the ecosystem and biodiversity, decreased primary productivity, and renewed soil carbon cycling (Schippers &Joenje, 2002; Harris, 2010; Wang et al., 2011). It also affected the dynamics of ecosystem services (Zhang et al., 2015; Zhang et al., 2016). Moreover, degradation can indicate plant species diversity and productivity by changing soil carbon cycling (Wang et al., 2014). Most previous studies on grassland degradation have focused on the vegetation status under enclosure in Inner Mongolia; Grassland degradation also has a crucial influence on soil respiration, which further affects carbon stocks and soil nutrient availability. Previous research has focused on macroscopic monitoring and evaluation to identify problems associated with degradation areas and grades (Tong et al., 2004; Wu et al, 2011). Degenerated grassland is extremely sensitive to the atmosphere and soil drought. Degradation is the main way to damage the ecosystem and alter its structure-process-functions.

We assume that there are sharp variations in carbon content of organs, soil water content in different levels of degradation, and that the carbon emission rate-soil feature (soil temperature and soil water content) relationship may be dramatically altered by changes associated with grassland degradation.
Based on these assumptions, we conducted a study at Xilingol League, Inner Mongolia, China, to research the dynamics change of plant and soil carbon stocks along gradients of grassland degradation and examine the effects of grassland degradation on carbon content of organs, soil water content and carbon emission rate. Grassland degradation is a complex process that integrates various aspects. Therefore our research focused on the essential traits of plants and soils to provide comprehensive assessment of grassland degradation and potential restoration methods.

2. Material and Methods

2.1. Study Sites and Experimental Design

According to plant coverage conditions (Wang et al., 1996a; Wang et al., 1996b), the grassland are classified into three groups: light degradation (LD) grassland with plant coverage >50%; moderate degradation (MD) grassland with plant coverage between 30%-50%; and severe degradation (SD) grassland with plant coverage <30%.

The field experiment on soil and vegetation were conducted from July to August 2015. In the research area, 74 sampling plots (100 m × 100 m) were randomly chosen every 20 km along a major road (Fig 1). Three typical sampling quadrats (1 m × 1 m) were placed to sample the vegetation according to plant coverage in each plot. The quantitative features included plant coverage and height, above-ground biomass, species composition, numbers and density, soil bulk density and soil water content. According to the division of the degree of degradation, 13 sampling plots were divided into LD grassland, 37 into MD grassland, and 24 into SD grassland of the 74 observed points.

2.2. Respiration Rate Measurements

The respiration rate was also measured in the sample plot with photosynthetic rate determined. The sample plots were classified into three types: bare land (Soil respiration rate), grass-cutting (Soil respiration rate plus root respiration rate) land and grass-retained land (Net carbon emission rate). An automated soil CO2 efflux measurement system (model LI-8150 multiplexer, LI-COR, Nebraska, USA) was used to measure the respiration rate. Two permanent PVC collars were installed in each type of land between July and August 2015. The respiration rate was continuously measured during 8:00-12:30 each day. Soil temperature and soil water content were also measured at a 10 cm depth outside of each chamber using the 8150-203 soil temperature sensor and soil moisture sensor, respectively.

3. Results

3.1. Response of Vegetation Features to Different Degeneration Grade

3.1.1. The Organ Carbon Content of Different Vegetative Organs.

The organ carbon content in the root increased and the leaf organ carbon content and the stem organ carbon content decreased with grassland degradation gradient. The root carbon content was 375.7 mg/g, 395.6 mg/g and 400.6 mg/g in LD, MD and SD grassland, respectively. The leaf carbon content was 454 mg/g, 448 mg/g and 436 mg/g in LD, MD and SD grassland, respectively. The stem carbon content was 442.4 mg/g, 435.5 mg/g and 430.8 mg/g in LD, MD and SD grassland, respectively. The root organ carbon content was significantly lower than that in the stem and leaf, and the root organ carbon content have the maximum range of change in the degradation gradient.

3.1.2. The Carbon Sequestration Ability in the Degeneration Grade.

Gross ecosystem productivity decreased from 15.51 µmol.m⁻².s⁻¹ in LD grassland to 9.7 µmol.m⁻².s⁻¹ in MD grassland and to 5.8 µmol.m⁻².s⁻¹ in SD grassland. The differences among the three levels of degeneration grasslands were significant (p<0.05). The marked decrease in ecosystem productivity in SD grassland showed that ecosystem productivity is seriously influenced by severe degradation. The net ecosystem exchange was -8.29 µmol.m⁻².s⁻¹, -3.14 µmol.m⁻².s⁻¹ and -1.57 µmol.m⁻².s⁻¹ in LD, MD and SD grassland, respectively. It suggesting that the carbon sequestration ability of the ecosystem decreases with the degree of degradation. The plant respiration rate decrease also decreased significantly with a higher level of
degradation. The respiration rate was 7.22 µmol.m\(^{-2}\).s\(^{-1}\), 6.56 µmol.m\(^{-2}\).s\(^{-1}\) and 4.22 µmol.m\(^{-2}\).s\(^{-1}\) in LD, MD and SD grassland, respectively. The difference in respiration rate between LD and SD grasslands was significant (Fig. 1).

![Figure 1. CO\(_2\) exchange rate for different degeneration grade steppes](image)

3.2. Response of Soil Features to Degeneration Grade

3.2.1. Soil Water Content. Overall, the soil water content in SD grassland was dramatically lower than in the LD or MD grassland of each soil layer (Fig. 2). At the 0-10 cm depth, the soil water content decreased from 13.1% in LD grassland to 9.1% in MD grassland and to 6.3% in SD grassland, with the difference between that in LD grassland being significantly higher than that in SD grassland. These results indicate that the surface soil water content decreased significantly as a result of severe degradation. In the second to fifth soil layers, the soil water content did not differ significantly between the different levels of degradation, suggesting that degradation does not affect the subsoil water content. The soil water content decreased with soil depth in LD and MD grasslands. In LD grassland, the soil water content in the first layer was significantly higher than in the second to fourth layers. The soil water content in the first layer was the highest. There were no significant differences between the five layers in MD grassland. In SD grassland, the soil water content did not exhibit a decreasing trend. Overall, the surface soil had more water content than the subsoil, and have the maximum range of change in the degradation gradient.

![Figure 2. Soil water content in five layers of different degradation grades](image)

3.2.2. Soil Organic Carbon Content. In the five soil layers, the soil organic carbon content decreased dramatically with degradation gradient, especially in LD grassland, which was significantly higher than in MD and SD grasslands (Fig. 3). The soil organic carbon content in MD grassland differed significantly with SD grassland at the 0-10 cm depth. These results suggest that the surface soil organic content differs significantly in different degradation levels.
At the same degradation level, the soil organic carbon decreased with soil depth. In LD grassland, the soil organic carbon exhibited a fast decrease, (i.e., 2.08 times from 18.04 mg/g at the 0-10 cm depth to 8.65 mg/g at the 40-50 cm depth). The soil organic carbon content at the 0-10 cm depth was significantly higher than at the 20-30 cm, 30-40 cm, and 40-50 cm depths ($p<0.05$). In MD grassland, the soil organic carbon was 2.95 times higher in the first layer than in the fifth layer, and was significantly higher than the other four depths ($p<0.05$). In SD grassland, the soil organic carbon content decreased 1.95 times (i.e., from 11.53 mg/g at the 0-10 cm depth to 5.85 mg/g at the 40-50 cm depth).

![Soil organic carbon content in different degradation grades](image)

**Figure 3.** Soil organic carbon content in different degradation grades

### 3.2.3. Soil Total Carbon Content

The soil total carbon content decreased significantly with degradation gradient at the 0-10 cm depth, which decreased from 26.03 mg/g in LD grassland to 17.66 mg/g in MD grassland and to 13.08 mg/g in SD grassland (Fig. 4). At the 10-20 cm depth, the soil total carbon content was highest in MD grassland and was significantly higher than in SD grassland ($p<0.05$). At the 20-30 cm depth, the soil total carbon content was 13.42 mg/g, 16.01 mg/g, 13.94 mg/g in LD, MD and SD grassland, respectively, although the differences were not significant. In the fourth to fifth layers, the soil respiration rates and soil total carbon content were significantly higher in SD grassland than in LD and MD grasslands ($p<0.05$). In LD grassland, the soil total carbon content decreased significantly with soil depth which in the first layer was 2.5 times higher than in the fifth layer and was significantly higher than the other four depths in LD grassland ($p<0.05$). In MD grassland, the soil carbon content showed a decreasing trend with soil depth, which decreased from 17.66 mg/g at the 0-10 cm depth to 10.71 mg/g at the 40-50 cm depth. In SD grassland, the soil total carbon content exhibited a clear increasing trend with soil depth, which was significantly higher in the fourth layer than in the second layer ($p<0.05$).

![Soil total carbon content in different degeneration grades](image)

**Figure 4.** Soil total carbon content in different degeneration grades

### 3.3. The Carbon Emissions from Different Components of the Ecosystem

In LD grassland, the soil respiration rates showed clear increasing trend from 8:00 -11:00, with the maximum soil respiration rate (11.88 µmol.m$^{-2}$.s$^{-1}$) occurring at 11:00 in grass-retained land. In MD and SD grasslands, the maximum soil respiration rate reached 7.79 µmol.m$^{-2}$.s$^{-1}$ and 5.91 µmol.m$^{-2}$.s$^{-1}$ at...
12:00, respectively. In MD grassland, the maximum soil respiration rate reached 8.32 µmol.m\(^{-2}\).s\(^{-1}\) in grass-retained land at half past eleven, and reached 5.28 µmol.m\(^{-2}\).s\(^{-1}\) and 2.78 µmol.m\(^{-2}\).s\(^{-1}\) in grass-cutting and bare land at twelve o’clock, respectively. In SD grassland, the soil respiration rate exhibited the same trend as LD and MD grasslands, which reached 1.11 µmol.m\(^{-2}\).s\(^{-1}\), 2.95 µmol.m\(^{-2}\).s\(^{-1}\) and 3.42 µmol.m\(^{-2}\).s\(^{-1}\) in bare land, grass-cutting land and grass-retained land, respectively. The soil respiration rate in the grass-retained land was similar to that in the grass-cutting land, suggesting that the plant respiration rate rarely affects grass-retained land of SD grassland. Overall, the soil respiration rate in grass-retained land was significantly higher than in grass-cutting and bare land.

In LD grassland, the soil respiration rate decreased significantly from 9.72 µmol.m\(^{-2}\).s\(^{-1}\) in grass-retained land to 6.27 µmol.m\(^{-2}\).s\(^{-1}\) in grass-cutting land and to 4.89 µmol.m\(^{-2}\).s\(^{-1}\) in bare land \((p<0.05)\). The same trend was observed in MD and SD grasslands. The soil respiration rate decreased significantly with degradation grade in the different land cover types. In bare land, the soil respiration rate in LD grassland was 5 times higher than in MD grassland. In the grass-cutting and grass-retained land, the soil respiration rate was 3 times higher in LD grassland than in MD grassland, suggesting that vegetation roots play an important role in the soil respiration rate in LD grassland.

4. Discussion

4.1. Changes in Carbon Content

It is well known that grassland degradation can easily cause decreased soil fertility (Wang et al., 2014). In this study, the soil organic carbon content was decreased significantly with increasing grassland degradation and the total soil carbon content also decreased at the 0-20 cm depth with degradation grade. The soil organic carbon content was extremely constrained by the vegetation conditions; the decrease in biomass with degradation grade immediately caused decrease in soil organic carbon content. Overall, the soil bulk density increased significantly with degradation gradient and the soil water content was significantly lower in SD grassland than in LD and MD grasslands. Moreover, the abrupt changes in these values between LD grassland and SD grasslands show that severe degradation has a profound effects on soil fertility and soil bulk density. Many studies have researched the effects of soil fertility on plant productivity (Clark&Tilman, 2008; De Deyn et al., 2009). The nutrient supply is a major limiting factor for community productivity (Reynolds&Haubensak, 2009). In the present study, community productivity was higher in LD grassland, which can be attributed to the sufficient fertility supply. The fraction of root biomass increased significantly with the grassland degradation gradient, suggesting that the allocation of resources changed from aboveground to underground. Community plant respiration decreased with degradation grade, which may be explained by the following two reasons: first, the community plant respiration may actually include the soil respiration, and grassland degradation caused the decline of root distribution in the soil, resulting in the decline of soil respiration; second, grassland degradation caused decreased plant coverage, which directly decreased plant respiration. The carbon sequestration ability of the *Stipakrylovii* community in SD grassland is higher than the *Stipa grandis* community in LD grassland (Wang et al, 2012). Soil respiration decreased significantly with degradation grade, indicating decreased carbon emission ability. These results correlate with the vegetation carbon absorption ability. Moreover, the difference in vegetation carbon absorption ability caused variations in root, stem and leaf carbon contents.

4.2. Relations between Carbon Emissions And Soil Water Content And Soil Temperature

Quadratic models were used to quantify the relationship between soil respiration rates and soil water content in each surficial vegetation from the three levels of degradation. The \(R^2\) of the models were higher than 0.6 and were significant at the 0.01 level. All second-order item coefficients of the quadratic curve equations were negative, indicating a soil water content threshold; the soil respiration rate increased with soil water content before the threshold value and decreased thereafter. The threshold differed slightly under various conditions. Each degradation grade displayed a linear relationship between soil respiration rate and soil temperature at 0-10 cm. The soil respiration rate exhibited a significant positive correlation with soil temperature at 0-10 cm, with \(R^2\) values ranging from 0.75 to
0.95. All regressions were significant at the 0.01 level. In LD and MD grasslands, the largest slope of regression was observed in grass-retained land. In SD grassland, the slope of regression was significantly lower in bare land than in grass-cutting and grass-retained land.

Soil respiration was controlled mainly by soil temperature in temporal variations and soil water content and soil organic carbon in spatial variations (Fan et al., 2015). Many studies have shown that significant exponential relationship between soil respiration and temperature (Zhang et al., 2010; Yu et al., 2011; Zhou et al., 2013). The effects of soil moisture on CO₂ efflux from soils have been described by numerous equations, including: linear, logarithmic, quadratic and parabolic functions (Davidson et al., 2000). The soil respiration quadratic is related to soil water content and exhibits a significant positive correlation with soil temperature in different degradation grades. Soil water content also affects soil respiration, mostly by altering the soil structure to change soil permeability, water circulation, soluble organic matter and effects the soil microbial activity (Moyano et al., 2013; Zhou et al., 2014). The soil respiration rate was mostly related to surface soil moisture in the growing season (Qi et al., 2010). Temperature also influenced soil respiration, and soil water content enhanced the response of respiration to temperature (Zhang et al., 2010). Wan et al (2005) found that an increase in temperature enhanced the soil respiration rate by promoting above-ground biomass, demonstrating a significant positive correlation between soil respiration rate and above-ground biomass. Moreover, an increase in temperature accelerated the decomposition rate of soil and litter fall, which increased CO₂ efflux (Luo et al., 2010). Degradation reduced plant-available water and decreased grassland productivity, which are associated with changes in soil structure and soil moisture regime (Zhao et al., 2011). Vegetation type can also affects soil respiration by controlling the root biomass and distribution of photo assimilates (Han et al., 2007; Bahn et al., 2010). The soil bulk density was the highest and soil water content was the lowest in SD grassland; therefore, soil respiration was the lowest in SD grassland.

5. Conclusions
Grassland degradation directly caused significant changes in the productivity, organ carbon content of different vegetative organs, soil bulk density and soil water content. The grassland community structure and plant characteristics changed significantly with degradation grade, which also affected the plant carbon content. Plant biomass dramatically affected the soil organic content. Ecosystem productivity was seriously affected by severe degradation. The relationship between carbon emission and soil features was influenced by degradation grade. The carbon sequestration ability of the ecosystem decreased with degradation grade.

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