SHRUB ENCROACHMENT ENHANCES CARBON STORAGE AND PLANT DIVERSITY IN THE DESERT STEPPE ECOSYSTEM

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(Received 31st Jan 2024; accepted 13th Jun 2024)

Abstract. Shrub encroachment onto grassland is a global problem, and thus the relationship between shrub encroachment and grazing disturbance needs to be clarified. In this study, we set up two treatments in China's desert steppe, including no grazing (CK) and heavy grazing (HG). We aimed to analyze the impact of grazing on carbon storage in shrublands and herbaceous communities. We utilized Real-Time Kinematic Positioning (RTK) and ground-penetrating radar (GPR) to detect and quantify aboveground / belowground biomass of *Caragana microphylla*. We also measured the biomass of grass. The resulting model for the aboveground biomass of *C. microphylla* was $y = 22.45e^{4.5562x}$, where x denotes the canopy area ($R^2 = 0.96$). The resulting model for the root biomass of *C. microphylla* was $y = 3\times10^{-5}x - 23.618$ ($R^2 = 0.99$), where x is amplitude. The coarse root / shoot ratios of the shrub were 8.06 and 8.92 in the CK and HG treatments, respectively. Heavy grazing significantly reduced the density and biomass of both *C.microphylla* and the broader community (shrub + grass) (P<0.05). The carbon stock of vegetation was significantly greater in shrubby grassland than in *Stipa breviflora* grassland (P<0.05). Our results show that shrub encroachment increased carbon storage and plant diversity in the desert steppe, while, at the same time, heavy grazing affect the shrub encroachment by *C. microphylla*.
Keywords: *real-time kinematic positioning, ground-penetrating radar, root biomass, Caragana microphylla, grazing*

Introduction

Greenhouse gas emissions have contributed to global climate warming (Wang et al., 2021), Overall, this has significantly affected the structure and function of ecosystems, particularly in the mid and high latitude regions of the Northern Hemisphere (Dang et al., 2023). In 2020, China announced their goals of beginning to continuously lower carbon emissions by 2030 and achieving carbon neutrality by 2060. Carbon sequestration and emission reduction are key measures in attaining these two goals. Steppe is the most widely distributed ecosystem in China, covering 30.5% of its land (Fang et al., 2018) and storing 28% of its total carbon stock in terrestrial ecosystems (Jin et al., 2015). Thus, steppe plays a key role in climate regulation and carbon cycling. Shrublands, which are distributed in the southwest, northwest, and in some parts of northern China, cover about one-fifth of the China's land (Ding et al., 2023; Li et al., 2024) and store approximately 30% of the carbon stock, thus representing an important carbon sink in addition to forests (Piao et al., 2009). Shrub encroachment is a product of climate change and human activity where shrubs invade steppe land and gradually come to dominate these ecosystems (Saintilan and Rogers, 2014; García, 2020; Liu, 2023). Shrub encroachment onto grassland is a global phenomenon characterized by an increase in the cover, density, and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_38913906

biomass of woody plants (Zhang et al., 2023). It is particularly prominent in arid and semi-arid zones (Knapp et al., 2007; Van Auken, 2009; Naito and Cairns, 2011). Some scholars insist that shrub encroachment significantly enhances the steppe's biomass (Zhao et al., 2023), while others have found that shrub encroachment reduces the coverage, density, and biomass of herbaceous plants (Liu et al., 2023).

Grazing in the steppe is closely linked to shrub encroachment (Cai et al., 2020). It is generally believed that shrub encroachment is promoted by overgrazing and selective feeding by livestock. Overgrazing can further lead to soil compaction, reduced soil water permeability and altered or redistributed and utilization of water and nutrients, all of which favor the expansion of shrub populations (Yang et al., 2022). Bar-Tolome (1989) suggests that the increase in shrub density in the western United States steepe over the past 160 years is associated with livestock grazing. Livestock can act as intermediaries for the dispersal of shrub seeds while feeding. Robinson et al. (2008) found that sheep were the primary intermediaries for seed dispersal during the invasion of *leguminous* shrubs in Western Australia. Another study indicates that grazing facilitates the spread of shrub seeds in the grassland of Southern Africa (Tews et al., 2004). However, other studies have argued that grazing is not a direct reason for shrub encroachment (Wei et al., 2019) and that it can even delay or limit (Zhang et al., 2019). Research has found that, in the Chihuahuan Desert, ungrazed dunes undergo a vegetation shift from dominance by herbaceous plants to dominance by shrubs (Cai et al., 2020). Similarly, a grazing prohibition in the temperate steppe of northern China resulted in shrub encroachment (Bach and Gojon, 2023). In sum, the role of grazing in regulating the shrub encroachment remains uncertain.

Roots are the primary source of soil carbon (Li et al., 2023). Thus, it is important to study root biomass distribution and dynamics to understand grassland productivity and carbon cycling. Research in the Patagonian steppe found that the root biomass of *Larrea Cav*. increased with grazing intensity and that shrub had dimorphic root systems (Larreguy et al., 2011). Other studies in alpine shrublands dominated by *Rhododendron thymifolium*, *Rhododendron capitatum*, and *Salix oritrepha* observed a decrease in shrub root biomass with increased grazing intensity (Wang et al., 2022). Overall, there is no consensus on the impact that grazing has on the root biomass and carbon sequestration of shrublands. Therefore, this study addressed the following questions: (1) What impact does grazing have on *C. microphylla* shrub encroachment onto desert steppe? (2) How do the biomasses of shrub and herbaceous plant communities change following shrub encroachment onto the grassland?

Shrub biomass is traditionally determination via harvesting (Yang et al., 2022). This involves measuring the partial biomass of a standard plant and then multiplying the density of plants to estimate the biomass of shrubs in a given area (Rong et al., 2023). Harvesting, however, is time-consuming and has low accuracy. The RTK carrier phase differential GPS technique offers one alternative, estimating aboveground biomass by measuring morphological parameters of a shrub. This method measures the morphological parameters of a shrub more accurately than the traditional method, but it also offers other advantages, such as simple operation, high accuracy, real-time capability, and high efficiency and precision (Liu, 2020).

Compared to measuring aboveground parts, measurement of root biomass during studies on the carbon cycling of grassland ecosystems is a bigger challenge(Zhang and Lu, 2021). Ground-Penetrating Radar (GPR), which is widely used for observing underground objects, has been utilized to aid in the location of coarse roots of trees and

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shrubs in the field to estimate root diameter, and to provide measurements for constructing biomass models (Guo et al., 2013; Wang et al., 2020). Compared to other non-destructive methods, GPR offers advantages such as portability, simple operation, rapid sampling, high detection resolution, and strong anti-interference. Overall, it provides more possibilities for long-term, in-situ root observation.

In this study, we selected *Caragana microphylla* shrublands in the Inner Mongolia desert steppe as the research subject. Utilizing RTK and GPR for in situ measurement of aboveground and root biomass of *Caragana* shrublands, we investigated the impact of grazing on desert steppe shrub encroachment and vegetation carbon storage. This study aimed to provide important theoretical support for the rational management of shrub-encroached steppe and for the improvement of grassland carbon sequestration in an effort to ultimately contribute towards China's dual carbon goals.

Materials and Methods

Study site

The study area was located at the Inner Mongolia Academy of Agriculture and Animal Husbandry Research Station, China (41°47′17″N, 111°53′46″E, alt. 1456m). The annual average precipitation is only 280 mm, with an annual accumulated temperature of ≥10 ℃ ranging from 2200 to 2500 ℃. The main soil type in the experimental site was Kastanozems soil. The dominant species at the site was *Stipa breviflora*, with *C.microphylla* being the primary shrub species.

Experimental design

The experiment commenced in 2004 with a randomized block design and four treatments: the no grazing control (CK), light grazing (LG), moderate grazing (MG), and heavy grazing (HG). Given the extent of root research, only two treatments were performed in full (CK, HG), with HG having a stocking rate of 2.71 sheep·hm²/a. Each treatment had three replicates, with each plot covering 4.4 hm² (*Figure 1*). The grazing period lasted from June 1 to December 1 each year. Adult Mongolian Wether sheep began grazing at 7:00 each day and returned to their pen at 19:00 each evening. A 10 m×10 m quadrat was demarcated within each plot to track the change in shrub biomass.

Figure 1. *The experimental paddock and block locations*

Measurement of aboveground shrub biomass

a. Obtaining morphological parameters of C. microphylla

From Aug. 27 to Sept. 1, 2023, the morphological parameters (area, perimeter, and diameter) of the shrub shoot were measured in the plot using the RTK method (*Figure 2*). Shrub shoots were harvested and placed into paper bags. The samples were dried for 48 hours at 65°C, and their dry weight was measured. A total of 17 standard medium-sized shrub bushes were measured and harvested during this experiment. For more details on how to measure shrub biomass using the RTK model, refer to Rong et al. (2023).

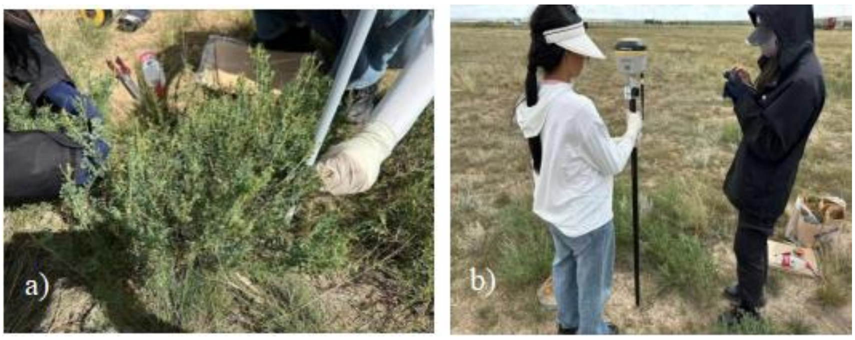

Figure 2. *Measurements of shrub height (a) and morphological parameter using RTK (b)*

b. Inversion of aboveground biomass for C. microphylla

The morphological parameters of *C. microphylla* individuals within the plots were precisely measured using RTK, and the coordinates of the locations of individuals were recorded. This data was used to draw a distribution map of *C. microphylla* and to estimate its shoot biomass.

Measuring the aboveground biomass of herbs

Five 1 m × 1 m quadrats were set up in each plot. All the herbs in these quadrats were harvested, and the samples were dried for 48 hours at 65°C to a constant weight, and then were weighed using a precision balance with an accuracy of 0.01.

Measuring the root biomass of **C. microphylla**

a. Sampling and processing of shrub coarse roots

A standard-sized shrub was selected for root sampling. Roots were dug out, selected, and cut into 30 cm lengths. Their fresh weight was measured first. The root segments were then sealed with melted wax and wrapped with plastic film. The diameter of each segment was measured at three points using a caliper. The roots were classified into six size classes: 0.5–1 cm, 1–1.5 cm, 1.5–2 cm, 2–2.5 cm, 2.5–3 cm, and >3 cm, with each group including 12 roots.

b. Burial of metal reflectors and root segments, and radar measurement of velocity

Burial of metal reflectors: In August, a test trench was dug with dimensions of 4.2 m × 1.5 m x 0.7 m (D). Six stainless steel plates measuring 10 cm × 10 cm × 0.1 cm (D) were buried at different depths: 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm. A 900

MHz antenna was used to observe the metal reflectors. The radar wave velocity is calculated according to the time it took for the transmission to travel from the surface to the root and the buried depth.

Next, six holes were drilled horizontally into the edge of each trench at horizontal intervals of 60 cm,, and at distances of 10 cm, 20 cm, 30 cm, 40cm, 50 cm, and 60 cm above the trench base. Each hole was 40 cm long, and one root was inserted in each (*Figure 3a*). This method ensured that roots of the same class could be buried at different depths without disturbing the original soil structure. The trench was then filled and compacted for measurement *(Figure 3b*).

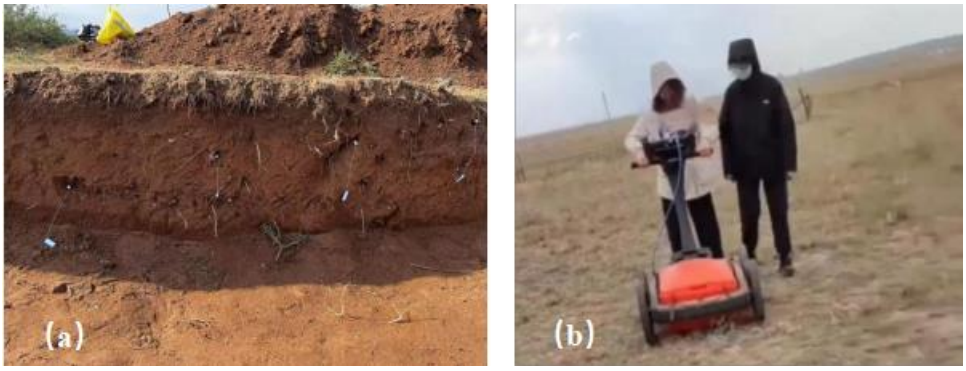

Figure 3. *A photograph of the roots on the edge of a soil trench (a) and a photograph of GPR in the field (b)*

c. Inversion of shrub coarse root biomass

In the plot, lines were set up at 20 cm intervals, and the original radar data of the *C. microphylla* shrub was collected along these lines using a GPR with a 900 MHz antenna to estimate the root biomass of *C. microphylla*. Further details on the method can be found in Cui et al (2013).

Measurement of herbaceous plant root biomass

After the aboveground parts of the herbaceous plants were removed from the quadrat roots were sampled using a 7 cm in diameter drill at depths of 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm. Samples were loaded into envelopes and brought back to the lab for processing. The samples were washed with tap water. Two types of sieves with pore sizes of 0.25 mm and 1.0 mm, were used to collect roots. Roots were dried for 12 h at 75 ℃ to a constant weight.

Statistical analysis of data

$$\text{Vegetation biomass} = \text{biomass of herbaceous plant community} + \text{biomass of shrub community} \quad \text{(Eq.1)}$$

The community biomass included both aboveground and coarse root biomass of *C.microphylla* and herbaceous plants. For carbon storage calculations, a conversion coefficient of 50% was used to represent shrub organic carbon content, and 45% was used to represent that of herbs (Shvidenko, 1996). The formula for carbon stock was:

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$$\text{Plant carbon stock} = \text{biomass} \times \text{carbon content coefficient} \quad \text{(Eq.2)}$$

Species richness

$$(S) = \text{the number of plant species in the quadrat} \quad \text{(Eq.3)}$$

Shannon-Wiener diversity index

$$(H) = -\sum(\text{Pi} \ln \text{Pi}) \quad \text{(Eq.4)}$$

Simpson diversity indexes

$$(D) = 1 - \sum_{i=1}^{s} P_i^2 \quad \text{(Eq.5)}$$

Pielou index

$$(J) = H / \ln S \quad \text{(Eq.6)}$$

In Equation 3, P_i is the importance value of the i_{th} species; the importance value is the mean value of relative plant height, relative cover and relative density.

ArcMap 10.5 was used to map the distribution of shrubs in the plots, while Microsoft Excel 2003 and Origin 2021 were used for graphing and statistical analysis. Paired T-tests were used to compare between the means of the CK and HG treatments at a significance level of 0.05.

Results

Impact of grazing on the density of C. microphylla

Heavy grazing significantly reduced the density of *C. microphylla* in the desert steppe (P<0.05, *Figure 4a*), but the herbaceous plant density did not change significantiy (*Figure 4b*). In the CK plots, the densities of *C. microphylla* and herbs were 0.23±0.08 plants/m² and 74.07±23.65 plants /m², respectively. In the HG plots, the densities were 0.04±0.01 plants /m² and 72.53±33.28 plants /m², respectively.

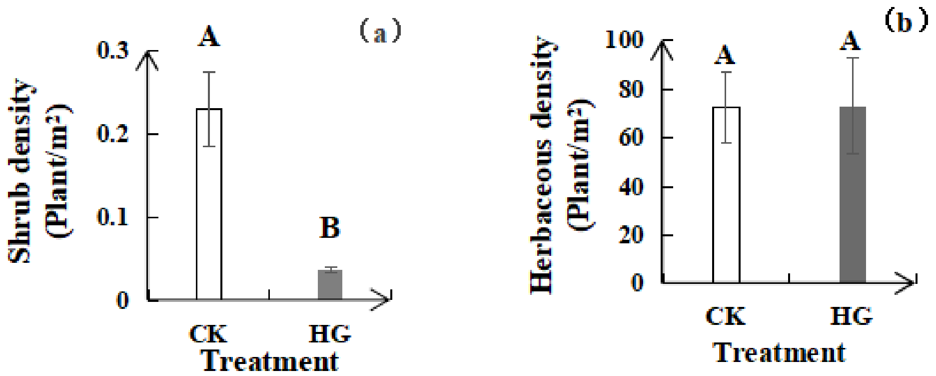

Figure 4. *Impact of grazing on the density of* C. microphylla *(a) and of herbs(b). Different capital letters indicated a significant difference between grazing treatments (P<0.05)*

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Developing the model of aboveground biomass in C. microphylla

We conducted a regression analysis to fit seven measurable factors extracted via RTK with the actual biomass of *C. microphylla* (y). These seven measurable factors were shrub height (H), crown width (D), crown area (S), product of crown width and height (D×H), product of crown perimeter and height (CH), and crown volume (V). The model was optimized through comprehensive analysis and comparison (*Figure 5*). An exponential function model was established, with S (plant crown area) as the independent variable: $y = 22.45e^{4.5562x}$.

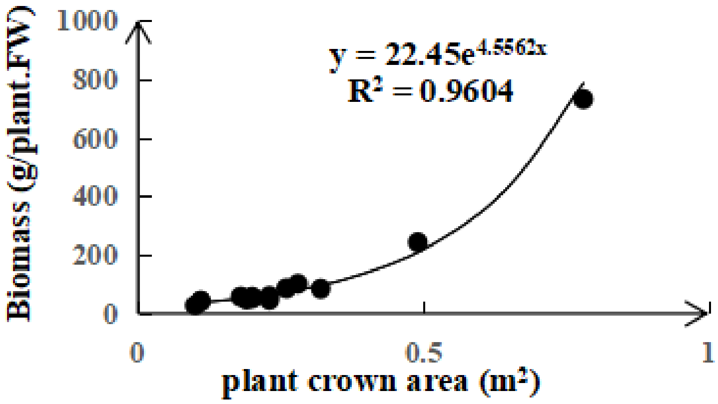

Figure 5. *Estimation model for aboveground biomass of* C. microphylla

Impact of grazing on aboveground biomass and carbon storage of C. microphylla *communities (shrubs and herbs)*

Community biomass represents the sum of shrub and herb biomass. The aboveground biomass and carbon storage of the community differed significantly between the two treatments. Heavy grazing significantly reduced the aboveground biomass and carbon storage of the community (*P*<0.05, *Figure 6*).

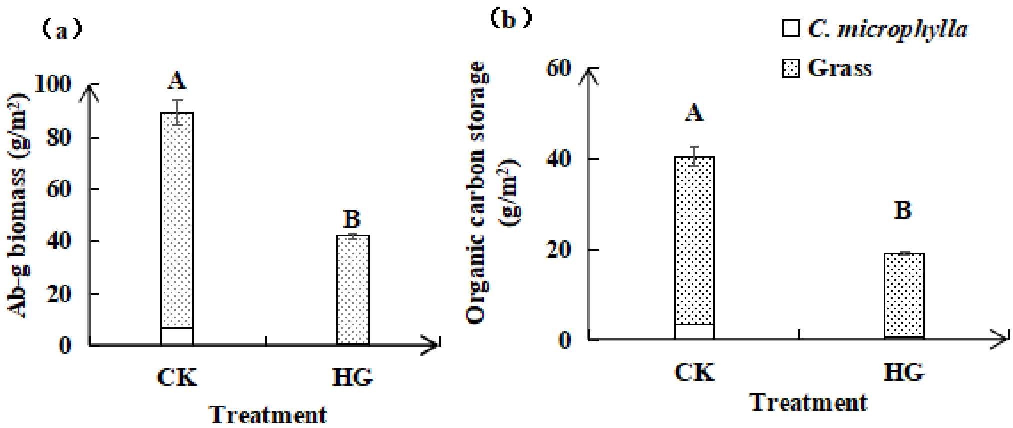

Figure 6. *Impact of grazing on aboveground biomass (a) and carbon storage (b) of* C.microphylla *communities. The same capital letters indicate no significant difference between grazing treatments (P>0.05)*

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The aboveground community biomasses were 89.15±8.39g/m² and 42.14±1.61g/m² in the CK and HG treatments, respectively. From this, the carbon storages of the respective treatments were derived as 40.47±3.76g/m² and 19.02±0.73g/m². In the CK treatment, the biomasses of *C. microphylla* and herbaceous plants were 6.98±4.61g/m² and 82.17±10g/m², respectively, and the carbon storages were derived as 3.49±2.31g/m² and 36.98±4.50g/m², respectively, in the HG treatment, the biomasses of *C.microphylla* and herbaceous plants were 1.02±0.03g/m² and 36.98±4.50g/m², respectively, and the carbon storages were derived as 0.51±0.01g/m² and 18.51±0.72g/m², respectively.

Impact of grazing on root biomass of shrubs and herbs

Developing a model for estimating the root biomass of C. microphylla

Based on the exponential regression model, the attenuation factor (a*) of the 900 MHz antenna was 0.526 for this site (*Figure 7a*). This variable helped compensate for the amplitude attenuation of the GPR reflection signals during root observation. A regression model for the root biomass of shrubs was constructed using the PA1 after attenuation compensation ($Y=3\times10^{\wedge-5X}-23.618$, *Figure 7b*).

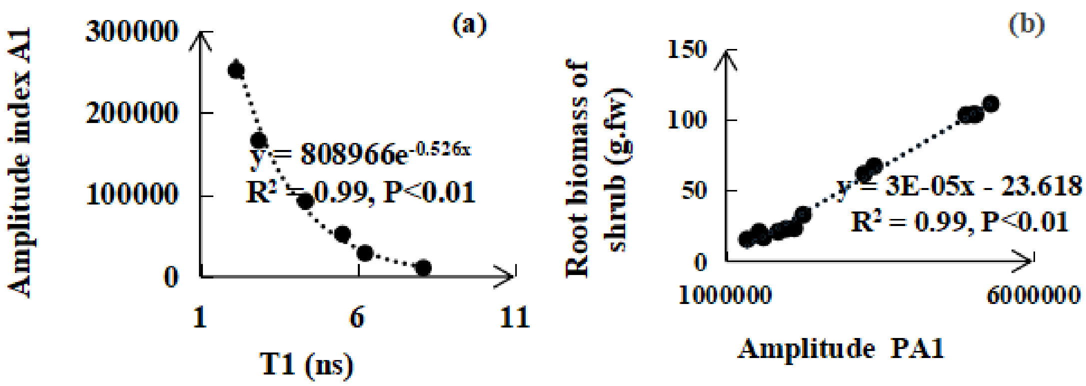

Figure 7. *Attenuation factor parameter (a) and root biomass model for* C. microphylla*(b)*

Impact of grazing on distribution and root biomass of C. microphylla

Figure 8 shows the spatial root distribution of the *C. microphylla* shrub. Under the CK treatment, the distribution of *C. microphylla* was patchy, dense, and widespread. In contrast, the spatial distribution of *C. microphylla* was sparse, had a limited range and appeared isolated in several small patches under the HG treatment (*Figure 8*). The coarse roots of *C. microphylla* in the CK and HG treatments covered an area of 5.44±0.48 m^2, and 3.52±0.08m^2, respectively (*Figure 9*). Heavy grazing significantly reduced the area covered by distribution range of shrub coarse roots.

Impact of grazing on root biomass and carbon storage of C. microphylla *communities*

Community root biomass represents the sum of shrub and herb root biomass. The root biomass of *C. microphylla* communities differed significantly between CK and HG treatments, and heavy grazing significantly reduced root biomass (*P*<0.05, *Figure 10*). The root biomasses of shrub communities were 865.73±83.18g/m² and 343.31±12.53g/m² (carbon storages were 392.39±36.93g/m² and 154.94±5.62g/m²) under the CK and HG treatments, respectively. Under the CK treatment, the root biomasses of *C. microphylla*

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and herbs were 56.28±32.05g/m² and 809.44±98.55 g/m² (carbon storages were 28.14±16.02g/m² and 364.25±44.35g/m²), respectively. Under the HG treatment, the root biomasses of *C. microphylla* and herbs were 9.10±1.15 g/m² and 334.21±12.97g/m² (carbon storages were 4.55±0.57g/m² and 150.40±5.84g/m²), respectively.

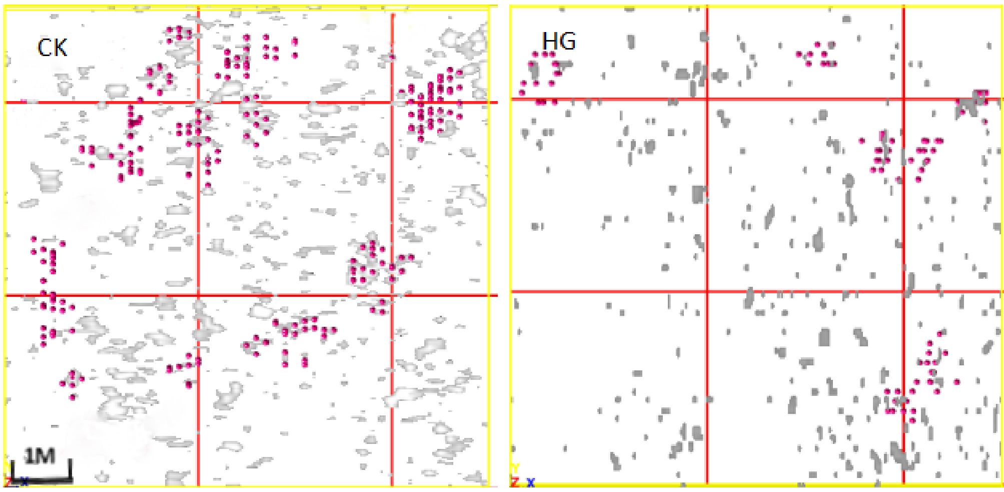

Figure 8. *Distribution of coarse roots of* C. microphylla *under the control (CK) and heavy grazing (HG) treatments.*

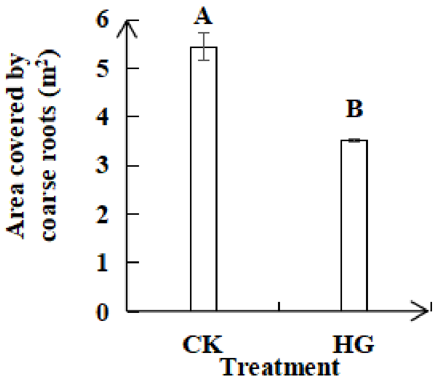

Figure 9. *Impact of grazing within 100m² on the area covered by coarse roots of* C. microphylla *in the desert steppe. The same capital letters indicated no significant difference between grazing treatments (P>0.05)*

Carbon storage in shrub-encroached grassland (shrubs and herbs) and in shrub-free grassland (herbs only)

Under the CK treatment, the carbon storage was significantly higher in shrub-encroached grassland than in shrub-free grassland (*P*<0.05, *Figure 11*). The carbon storage in shrub-encroached grassland was 432.86±39.88g/m², while that in shrub-free grassland was 303.91±39.88 g/m². Under the HG treatment, there was no significant difference between the carbon storage in shrub-encroached grassland and in shrub-free grassland (*P*=0.68), with the carbon storage 173.96.42±6.34 g/m² in shrub-encroached grassland and 171.42±10.70 g/m² in shrub-free grassland.

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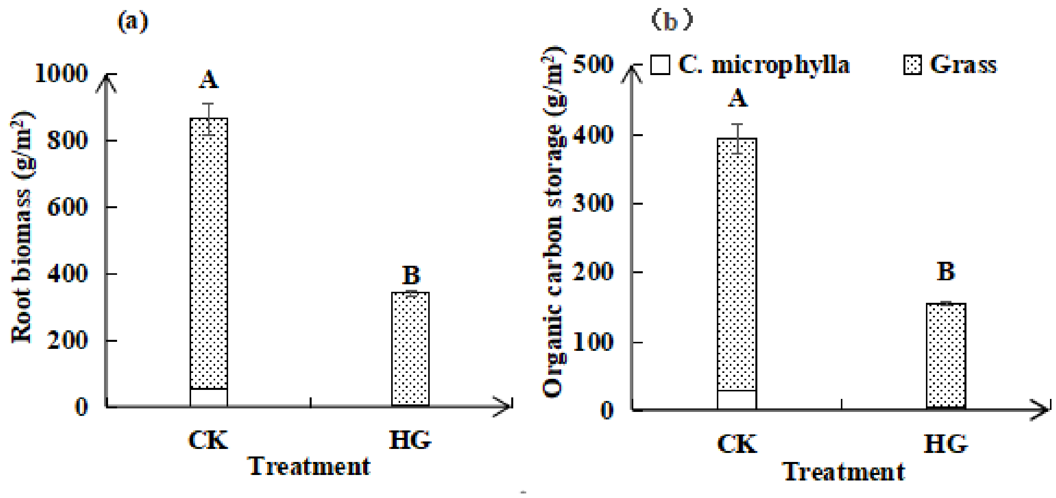

Figure 10. *Impact of grazing on root biomass and carbon storage of communities. The same capital letters indicated no significant difference between grazing treatments (P>0.05)*

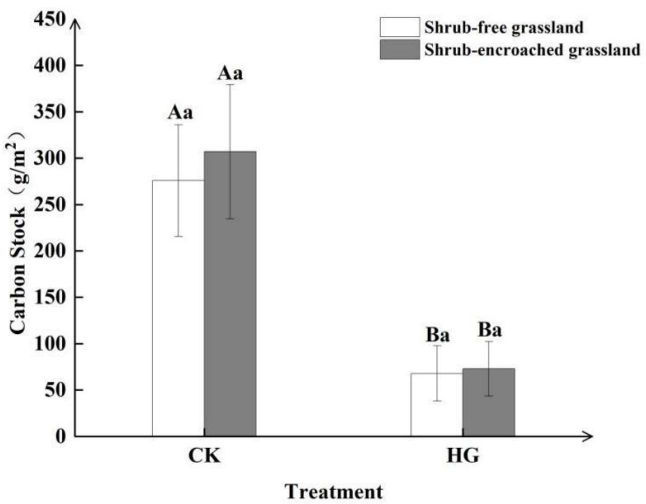

Figure 11. *Comparison of carbon storage between shrub-encroached grassland and vegetation and shrub-free grassland vegetation. The same uppercase letters indicate that there is no significant difference between grazing treatments (P>0.05), and the same lowercase letters indicate that there is no significant difference between different community types (P>0.05)*

Effect of grazing and shrub encroachment on plant community diversity

The Simpson dominance index and the Shannon-Wiener index were significantly higher under the CK treatment than under the HG treatment (P<0.05, *Table 1*). Pielou index and species richness did not differ significantly between the CK and HG treatments (P>0.05). The Simpson index, Shannon-Wiener index and species richness were all greater in CK subplots with shrubs than those lacking shrubs. In summary, the shrub encroachment of the CK treatment lead to improvements in plant community dominance and diversity, but it had no significant effect on plant Pielou evenness.

***Table 1.** Effects of different grazing treatments on plant community diversity in the desert*

Treatment	Simpson	Pielou	Shannon-Wiener	Species Richness
CK（shrubs & herbs）	0.61a	0.79a	1.11a	4.23a
HG	0.54b	0.75a	0.96b	3.83a
CK (shrub)	0.66A	0.78A	1.33A	5.73A
CK (herbs)	0.61B	0.79A	1.11B	4.27B

Note: The same lowercase letters indicated that there was no significant difference between different grazing treatments (P>0.05). The same capital letters indicated no significant difference between CK subplots (P>0.05)

Discussion

Impact of grazing on C. microphylla *shrub encroachment onto the desert steppe*

Li et al. (2023) found that the proportion of fine root biomass to total root biomass in 6~31-year old *Caragana* shrubs ranged from 5.0%–10.0%. Therefore, in this study, we did not harvest all the roots of *C. microphylla.* Instead we only measured the coarse roots greater than 0.5 cm in diameter. We found that the coarse root biomasses of *C. microphylla* were 56.28±32.05 g/m^2 and 9.10±1.15 g/m^2 under the CK and HG treatments, respectively, and the root to shoot ratios(R/S) were 8.06 and 8.92, respectively, Hu et al. (2020) found that the root biomass of *C. microphylla* in desert steppe was 432.83±395.59 g/m^2, and the R/S was 8.74. The R/S in our study were similar to theirs. In this study, we found that the root-shoot ratio of herbs was 9.8, and the root biomass of herbs was nearly ten times greater than the aboveground biomass. This was attributed to the relatively arid and barren desert steppe conditions at this experimental site. In arid areas, plants increase their root biomass to better adsorb the water (Wang et al., 2021), and they expand their root system to absorb more nutrients (Bindraban et al., 2015; Kleinert et al., 2018).

In this study, RTK was used to find the positions at which to measure the standard shrub. Compared with the traditional methods, such as measurement by a ruler or counting the number of standard shrub, the application of RTK improves data accuracy and reduces the active measuring time (Rong, 2023). After measurement, we found that heavy grazing significantly reduced the density, biomass and carbon storage of *C. microphylla*. This can be attributed to the selective foraging by sheep and the plant palatability (Narantsetseg et al., 2014). Sheep feed on palatable shrubs, such as *Caragana microphylla* (Zhou, 1990), or on young shrub saplings, thereby reducing the regeneration capacity of shrubs. A group of sheep trampling during a heavy grazing scenario will compact the soil, making it difficult for the roots to grow (Lynch et al., 2022) and, ultimately, affecting the survival of the shrub. At the same time, sheep trampling also reduces air and water permeability of the soil, thus making the soil more susceptible to weathering and water erosion and also reducing the carbon storage capacity of the soill (Shah, 2017). Although sheep excreta, a side effect of grazing, provide nutrients to shrubs to a certain extent, excessive excreta, which can occur under a heavy grazing scenario, negatively impact the soil and shrub growth (Zajícová, 2019). Heavy grazing inhibits shrub the growth and reproduction and can overall lower the number of seeds (Tadey, 2016). In general, heavy grazing reduces the carbon storage capacity of *C. microphylla* by reducing its competitiveness, destroying soil structure, and hindering seed transmission.

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DOI: http://dx.doi.org/10.15666/aeer/2205_38913906

Comparison of carbon storage between shrub–encroached steppe and shrub-free steppe

This study demonstrated that in an ungrazed grassland, the carbon storage of vegetation in shrub-encroached grassland has significantly greater carbon storage capacity than shrub-free grassland. Wang et al. (2022) also found that *C. liouana* shrub encroachment significantly increased the carbon storage capacity of the aboveground vegetation in the desert steppe. Because desert steppe shrubs are bigger and have a greater biomass than desert steppe herbs, shrub encroachment, which replaces the original herbs, leads to an increase in the carbon storage of the grassland ecosystem (Petrie et al., 2015). Li et al. (2016) found that soil organic carbon content increased in semi-arid regions, but the soil organic carbon content had a greater rate of increase in the legume shrub grassland than that in the non-legume shrub grassland. This was because the shrub litter augmented the input of soil organic matter, thus increasing the carbon storage of the soil as well (Montané et al., 2010; Castellano et al., 2015). Shrub roots have greater biomass and a slower decomposition rate than herbs, which helps improve the carbon accumulation in the soil (Lai et al., 2016). At the same time, the growth and dispersal of shrubs alters the original water and nutrient cycles and promotes carbon storage throughout the ecosystem (Mekonnen et al., 2021). Therefore, shrub encroachment increases carbon storage capacity in the desert steppe.

Effects of shrub-encroachment on plant diversity

We found that shrub encroachment by *C. microphylla* helped improve the dominance and diversity of vegetation, which was consistent with the results of Archer et al. (2017) regarding shrub encroachment in grasslands of America, Australia and South Africa. Shrub encroachment leads to invasive species becoming dominant in resource acquisition or spatial occupation (Crall et al., 2006) and, thereby increases community dominance. The well-developed roots of shrubs stabilize soil, reduce erosion and improve soil quality (Anteneh et al. 2017), all of which foster the growth of herbs. Invasion by shrubs can also provide shade and windshields for herbs, thus helping the herbs to survive (Andreu et al. 2009). At the same time, shrub litter can augment the soil organic matter content (Montané et al., 2010; Castellano et al., 2015), thereby supporting a wider range of herbs. This study found that shrub encroachment had little effect on vegetation evenness. Song and Wang (2022) also found that when the density of shrubs was too low, low vegetation evenness may ensue.

Conclusion

In the desert steppe, heavy grazing significantly reduced the aboveground and root biomass of *C. microphylla*, as well as its carbon storage (P<0.05), and thus inhibited encroachment by *C. microphylla*. However, also under heavy grazing, the vegetation biomass and carbon storage were significantly greater in the shrub-encroached grassland than in the shrub-free grassland (P<0.05). This suggests that shrub encroachment can increase carbon storage capacity and plant diversity in the desert steppe, but also that heavy grazing can inhibit the *C. microphylla* encroachment.

Acknowledgements. This study was supported by the Center for Leading Local Science and Technology Development Plan (2021ZY0020), the National Science Foundation of China (32160331), Inner Mongolia key Laboratory of grassland management and utilization (2022PT0003) and the Project for Revitalization of Inner Mongolia through Science and Technology (2021CG0020), and as well as the IWHR Research and Development Support Program (MK0145B022021). This work was also supported by the Open Research Fund of Yinshanbeilu Grassland Eco-hydrology National Observation and Research Station, China Institute of Water Resources and Hydropower Research (Grant NO.YSS202109).

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