Impact of livestock grazing management on carbon stocks: a case study in sparse elm woodlands of semi-arid lands

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Livestock grazing is a widespread practice in human activities worldwide. However, the effects of livestock grazing management on vegetation carbon storage have not been thoroughly evaluated. In this study, we used the system dynamic approach to simulate the effects of different livestock grazing management strategies on carbon stock in sparse elm woodlands. The livestock grazing management strategies included rotational grazing every 5 years (RG5), prohibited grazing (PG), seasonal prohibited grazing (SPG), and continuous grazing (CG). We evaluated the carbon sequestration rate in vegetation using logistical models. The results showed that the carbon stock of elm trees in sparse woodlands was 5-15 M g ha^{-1}. The values of the carbon sequestration rate were 0.15, 0.13, 0.13, and 0.09 Mg C ha^{-1} $year^{-1}$ in RG5, PG, CG, and SPG management, respectively. This indicates that rotational grazing management might be the optimal choice for improving vegetation carbon accumulation in sparse woodlands. This study contributes to decision-making on how to choose livestock grazing management to maintain higher carbon storage.

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Abstract

Livestock grazing is a widespread practice in human activities worldwide. However, the effects of livestock grazing management on vegetation carbon storage have not been thoroughly evaluated. In this study, we used the system dynamic approach to simulate the effects of different livestock grazing management strategies on carbon stock in sparse elm woodlands. The livestock grazing management strategies included rotational grazing every 5 years (RG5), prohibited grazing (PG), seasonal prohibited grazing (SPG), and continuous grazing (CG). We evaluated the carbon sequestration rate in vegetation using logistical models. The results showed that the carbon stock of elm trees in sparse woodlands was 5-15 M g ha^{-1}. The values of the carbon sequestration rate were 0.15, 0.13, 0.13, and 0.09 Mg C ha^{-1} $year^{-1}$ in RG5, PG, CG, and SPG management, respectively. This indicates that rotational grazing management might be the optimal choice for improving vegetation carbon accumulation in sparse woodlands. This study contributes to decision-making on how to choose livestock grazing management to maintain higher carbon storage.

Keywords: biomass; elm trees; Horqin Sandy Land; logistic model; system dynamic approach

Introduction

Global warming, which is primarily caused by excessive emissions of CO_2, has attracted worldwide attention (Lv et al.,2019). One important strategy for reducing anthropogenic CO_2 emissions is carbon storage (Min et al.,2018). The terrestrial biosphere, a repository of approximately 2,000 Gt of carbon, plays a crucial role in carbon storage (Ruhland and Niere,2019). Vegetation, as a major component of the terrestrial biosphere, is responsible for a large proportion of carbon storage (Hou et al., 2015; Fu et al.,2019). Trees, as the largest and longest-lived plants, are particularly important for carbon storage (Zellweger et al., 2022). Vegetation plays a pivotal role in regulating the carbon cycle and storing carbon primarily by absorbing CO_2 through photosynthesis and subsequently releasing some of it back into the atmosphere through respiration (Qiu et al, 2020). Therefore, strategies that enhance vegetation carbon storage can effectively mitigate global warming (Iglesias et al.,2012; Piao et al., 2018).

Arid and semi-arid areas together constitute almost one-third of the world's land area (Zhang et al.,2018). In these regions, livestock grazing is a prominent human activity. It is considered as an effective approach for regulating carbon storage in soil and vegetation (Chen et al., 2012; Wu et al., 2014). The effects of grazing exclusion and its duration on carbon storage in soil and vegetation have been studied in previous studies (Medina-Roldan et al., 2012; Xiong et al., 2016; Wang et al.,2018). For example, the effects of fencing on carbon stocks were explored in degraded alpine grasslands (Li et al.,2013), and the duration of exclosure practice was investigated in a degraded grassland in China (Li et al.,2012).

Grazing management plays a pivotal role in shaping the carbon dynamics of terrestrial ecosystems (Polley, et al., 2008). At the most fundamental level, grazing alters plant biomass, which directly impacts the amount of carbon that vegetation can sequester from the atmosphere (Farrell et al.,2015). For instance, moderate grazing can stimulate plant growth due to the removal of old plant material, which can pave the way for new shoots. This often results in a net increase in photosynthetic activity and, thus, increased carbon capture. In contrast, the balance of different plant species, dictated in part by grazing intensity, can also influence the carbon storage potential of an ecosystem, as different plants possess varying carbon sequestration capacities (Zhang et al.,2017). Therefore, understanding the intricacies of grazing management is paramount not just for ecosystem health, but also for optimizing the carbon sequestration potential of landscapes.

Recently, the difference in the effects of livestock grazing management on ecosystems has attracted much attention (Eldridge and Delgado-Baquerizo, 2017). Studies have reported on the effects of seasonal prohibited grazing and grazing intensities on soil organic carbon stock in Mongolian grasslands (He et al., 2011; Chang et al., 2015). Other management practices, including grazing period, number of burns, and slashes, have been considered in a dry tropical region of western Mexico (Trilleras et al.,2015). Although the effects of several grazing management practices have been reported separately in case studies, the role of grazing management in carbon stock, especially in vegetation, has not been fully compared.

Given the fragmented nature of current research on grazing management's effect on carbon stock, there's a pressing need for a more comprehensive approach to these investigations. The model simulation approach presents a robust avenue to address this gap. Through modeling, we can holistically evaluate the impacts of varied livestock grazing management practices against a unified benchmark, enabling more thorough comparisons. Firstly, models in plant population and vegetation dynamics have been widely reported, providing a framework for models (Griffith and Forseth,2005; Marano and Collalti, 2020). Secondly, the quantitative relationship between carbon stock and plant biomass has been explored (Bayen et al, 2020; Brown et al.,2020). Lastly, experimental studies have provided some evidence to verify the simulating models (Li, 2006; Zhao et al.,2016).

Understanding the impacts of grazing management on vegetation carbon storage is not only of academic interest but also holds profound implications for policy formulation and the evaluation of ecosystem services. Firstly, optimizing carbon storage in ecosystems serves as a countermeasure to rising atmospheric CO_2 concentrations, potentially mitigating the impacts of global warming (Piao et al., 2009). Moreover, the retained carbon stock is intrinsically linked to the broader spectrum of ecosystem services, underpinning their value and functionality (Yang and Tang, 2019). As grazing practices directly modulate the carbon balance of an ecosystem, they become pivotal tools in enhancing ecological services.

Carbon sequestration rates serve as a crucial aspect in understanding the role of grazing management in determining carbon fixation within vegetation. The carbon sequestration rate is an insightful metric to represent the annual carbon accumulation in vegetation (Wang et al., 2014; He et al., 2017). Calculating vegetation carbon sequestration rates is conventionally achieved by examining the average change in carbon stock over a designated time span (Li et al., 2023). In recent studies, it has been proposed that the relationship between vegetation carbon stocks and carbon sequestration rates can be effectively described using logistic functions (Dong, et al., 2021). Utilizing logistic functions to determine carbon sequestration rates proves advantageous as it encompasses non-linear growth patterns, offering a comprehensive perspective on carbon accumulation dynamics over time.

The primary objective of this study was to assess the impacts of livestock grazing management on vegetation in semi-arid regions from two perspectives: carbon stock and carbon sequestration rates. Our approach involved establishing a system dynamics model with multiple life-history stages to simulate the effects of grazing managements on plant biomass. By understanding the relationship between biomass and carbon stock, we could determine the carbon stock. Subsequently, by employing a logistic model linking carbon stock to carbon sequestration rates, we estimated the latter. This research provides a holistic methodology to comprehend the multifaceted repercussions of grazing management on carbon dynamics, thereby offering valuable insights for sustainable land-use strategies in semi-arid environments.

Materials & Methods

This study was conducted in the Wulanaodu region (42° 29' -43° 06'N, 119° 39' -120° 02'E, 480m a.s.l.), located in the Horqin Sandy Land, one of the largest sand lands in China (Tang et al., 2014). This region is a typical landscape composed of active sand dunes, stabilized sand dunes, and inter-dune lowlands. The region has a semi-arid climate, with a mean temperature of 23 ℃ in July and -14℃ in January (Zhang et al., 2016). Sparse elm woodlands are the original vegetation community in this region, and *Ulmus pumila* is the dominant tree species in these woodlands (Tang, 2020). Besides *U. pumila* trees, there are also sparsely distributed shrubs and herbs, whose biomass is far less than *U. pumila* trees (Zhao et al.,2016).

2.1 System dynamic model

A system dynamic model was constructed, taking into account the five stages of the U. pumila life cycle, i.e., seed (i=1), seedling, juvenile, mature, and over-mature (i=5) tree stages. In this model, the seed stage is linked to the mature and over-mature stages, as seeds are produced in these two stages. The seeds become seedlings at a specific germination rate. *U. pumila* trees die at a stage-specific rate, except for the seed stage. At the over-mature stage, no transition is made to the next stage; as a result, the over-mature stage is the last in the U. pumila life cycle. The equations depicting the elm life cycle are shown below (Tang and Busso, 2018).

$$\frac{dN_i}{dt} = \sum_{i=4}^{5} B_i \cdot N_i - TP_i \cdots\cdots\cdots\cdots \; for\ seed\ stage \quad (1)$$

$$\frac{dN_i}{dt} = \begin{cases} TP_{i-1} \cdot N_{i-1} - (D_i + TP_i) \cdot N_i, N_i < M_i \\ 0 \quad ,N_i \geq M_i \end{cases}, i = 2,\cdots,n-1 \quad (2)$$

$$\frac{dN_i}{dt} = \begin{cases} TP_{i-1} \cdot N_{i-1} - D_i \cdot N_i,\ N_i < M_i \\ 0 \quad ,N_i \geq M_i \end{cases} \cdots\cdots\cdots\cdots i = n \quad (3)$$

$$M_i = \frac{P_i}{WC_i}, \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots i = 2,\cdots,n \quad (4)$$

Here, N represents the number of individuals at each of the five stages, while B and D represent birth and death rates, respectively. TP stands for the transition probability (i.e., the probability associated with an elm population at one age-stage shifting to another age-stage). WC represents the water consumption per individual at each of the developmental stages, except for the seed stage. P represents precipitation, which follows a normal distribution, whose parameters, i.e., mean and variance, were calculated according to long-term collected data. Besides the parameters mentioned above, other parameters include death rate, seed germination rate, and the period of each morphological stage. The values of all parameters used in the system dynamic model are shown in Table 1.

Table 1 is here

2.2 Carbon stock

The carbon stock of elm trees was calculated using Equation 5, where the C content of elm trees was calculated by considering different parts of the elm trees, including leaves, twigs, stems, and roots.

$$Total\ C = \sum_{i=1}^{4} C\ concentration_i \times Biomass_i \qquad (5)$$

In equation 5, i ranges from 1 to 4, representing the leaf, twig, stem, and root separately. The C concention of each part of the elm trees was specifically measured in a previous study (Zhao et al.,2016, Table A.2). The biomass in each part was calculated using allometric equations, the formation of which follows equation 6. Species-specific allometric equations based on tree diameter at breast height (DBH) were applied to estimate the biomass.

$$Biomass_i = a_i \times DBH^{b_i} \qquad (6)$$

Where a_i and b_i are special parameters measured in a previous study (Li, 2006, Table 2), i from 1 to 4 representing leaf, twig, stem, and root separately. DBH was estimated using equation 7, with the age of the elm tree serving as the independent variable.

$$DBH = A + B \times age \qquad (7)$$

Where A and B are estimated using data from a previous study and their values here are -0. 1698 and 0.3839 (Niu, 2008).

2.3 Carbon sequestration rate

The vegetation Carbon sequestration rate (Rseq) was obtained with a logistic model, where the Carbon sequestration rate serves as a parameter and is estimated using equation 8.

$$Carbon\ stock = K \times N_0 \times \frac{e^{R_{seq} \times age}}{K + N_0 \times (e^{R_{seq} \times age} - 1)} \qquad (8)$$

In equation 8, carbon stock refers to the amount of carbon stored in the vegetation at a given age. K is the carrying capacity, representing the maximum potential carbon stock achievable by the vegetation in the given conditions. N_0 is the initial carbon stock at age 0, representing the amount of carbon present in the vegetation at the time of planting or the start of observation. R_{seq} is the C sequestration rate, which governs the rate at which the vegetation assimilates atmospheric carbon. Here K, N_0 and R_{seq} are parameters needed to estimate.

Table 2 is here

2.4 Scenarios analysis

We evaluated the effects of grazing management on carbon stock in sparse elm woodlands. In this study, we considered four scenarios of grazing management, i.e., rotational grazing every 5 years (RG5), prohibited grazing (PG), seasonal prohibited grazing (prohibition in periods from March to July, SPG), and continuous grazing (CG). Continuous grazing increases elm seed production and decreases elm seedling densities in sparse elm woodlands in a previous study (Tang et al., 2014). Seasonal prohibited grazing influences elm seedlings but does not influence seed production, as seed dispersal mainly occurs in May (Liu and Tang, 2018). Meanwhile, rotational grazing every 5 years works as continuous grazing once every five years. The specific values are shown in Table 1.

2.5 Data analysis

The system dynamic model was formulated and simulated using professional SD software (Vensim PLE). A unit-consistency test, which checks for agreement among units, was used to validate this model. It was automatically completed in the Vensim package (Tang and Li, 2018).

The models in equations 7 and 8 were estimated using the R programming language (R Core Team, 2022). The best-fit model derived from equation 7 is $DBH = -0.169 + 0.383 \times age$ (F-statistics= 431.8, adjusted R2= 0.837, P <0.05). The parameters were significant at a critical value (P <0.05). The standard error (SE) of the estimated parameters and residual standard error (RSE) of the logistical model were reported.

Results

3.1. Effects of grazing management on carbon stock

In the first ten years, the carbon stock of elm trees was almost the same under all four management techniques. From the tenth year to a hundred years, the carbon stock of elm trees in RG5 and PG management was higher than in CG and SPG management. From the twentieth year to a hundred years, the carbon stock of elm trees under CG management was more substantial than under SPG management.

When comparing RG5 to PG management, the carbon accumulation in the PG treatment surpassed that of the RG-5 between the 70th and 80th years, but was diminished between the 90th and 100th years. In contrast, when comparing RG5 with CG management, carbon sequestration in CG was inferior to that in RG-5.

From the beginning to the 80th year, the ability to store carbon increased under RG5, PG, CG, and SPG management. After the peak, the ability to maintain carbon stock decreased under RG5, PG, and CG management, while the ability to maintain carbon stock remained steady under SPG management (Figure 1).

Figure 1 is here

The carbon stock of elm trees remained below 5 M g ha^{-1} throughout the simulation period under SPG management. In contrast, the carbon stock of elm trees exceeded 5 M g ha^{-1} almost from the fiftieth year and onwards under CG management. Additionally, the carbon stock of elm trees exceeded 5 M g ha^{-1} after the 20th year under RG5 and PG management. Furthermore, the carbon stock of elm trees under RG5 and PG management ranged between10 and15 M g ha^{-1} after the 40th year (Figure 1).

3.2. Effects of grazing management on carbon sequestration rate

The carbon sequestration rate was significantly related to the carbon stock in elm trees under all four management techniques. The estimated values of the carbon sequestration rate in elm trees were 0.15, 0.13, 0.13, and 0.09 Mg C ha^{-1} $year^{-1}$ in RG5, PG, CG, and SPG management, respectively. Additionally, under all four management techniques, the K values were also found to be significantly related to the carbon stock in elm trees (Table 3, Figure 2).

Figure 2 is here

Table 3 is here

Discussion

4.1 Carbon stock in elm trees

In RG5 and PG management, the carbon stock in elm trees is faster and in greater quantities than in CG and SPG management. This suggests that RG5 and PG are the preferred choices for maintaining steady carbon storage in elm trees. This result is consistent with a previous study, where elm seedlings and sapling densities were found to be significantly higher in fenced plots than in grazed plots (Tang et al.,2014). This is likely due to grazing threats to the growth of seedlings and saplings (Bergmeier et al.,2010). Similar results were also found in a similar landscape, the tropical savanna, where long-term grazing was found to have reduced vegetation biomass (Ngatia et al.,2015).

According to this study, the carbon stock of elm trees is 10-15 M g ha^{-1} in mature-stage sparse woodlands under prohibited grazing management. This result is consistent with an experimental study in sparse woodlands, where the carbon stock of elm trees was found to be 15.57 M g ha^{-1} in fenced plots (Zhao et al., 2016). These consistent results suggest that the system dynamic approach is effective in simulating changes in the carbon stock of plant populations. In previous studies, the system dynamic approach has been used to simulate various aspects of plant populations, including the carbon cycle, hydrological processes, and population dynamics (Mukherjee et al., 2013; Ouyang et al., 2016; Tang et al, 2016). This study expands the application of the system dynamic approach by incorporating it in the calculation of vegetation carbon sequestration and evaluating the effects of specific factors.

The results reveal a notably low carbon sequestration associated with the SPG treatment (Figure 1). A plausible rationale for this observation hinges on the period spanning March to July, which is likely the predominant growth phase for regional vegetation. By prohibiting grazing during these crucial months, an excessive proliferation of herbs may ensue, which could subsequently impede the germination and establishment of elm tree seeds (Tang et al., 2014). Such a reduction in the available seed source inevitably results in a decline in the population of elm trees. This chain reaction, commencing from the lowered elm population, can be linked to the observed decrement in vegetation carbon sequestration within the SPG treatment.

Meanwhile, the carbon accumulation observed in the PG treatment appears to surpass that of the RG-5 treatment between 70 and 80 years. This can potentially be attributed to the enclosure practices, which tend to bolster biomass accumulation, yielding a slight elevation in carbon sequestration compared to RG5 within that timeframe. Yet, as the duration of enclosure prolongs, an elevated population density ensues, inciting heightened interspecific competition. This amplified competition paves the way for increased individual mortality, leading to a reduction in the aggregate population biomass, and, in turn, a subsequent decline in carbon accumulation.

Grazing management can influence soil carbon stock by regulating soil organic carbon and soil microbial carbon (Li, et al.,2013). The effects of grazing exclusion on soil carbon stock are more commonly reported compared to other grazing management techniques (Li, et al., 2012). A possible reason for this is that grazing and grazing exclusion are the most commonly used grazing management techniques in grasslands and degraded lands, and it is relatively easier to establish designed experimental plots for these methods. Rotational grazing management has great potential for maintaining vegetation carbon stock, and its effects on soil carbon stock should be fully considered.

4.2 Carbon sequestration rate under grazing managements

Elm trees exhibited varying carbon sequestration rates under different management practices: 0.15, 0.13, 0.13 and 0.09 Mg C ha^{-1} $year^{-1}$ in RG5, PG, CG, and SPG, respectively. This clearly highlights RG5 management as the most efficient in terms of carbon sequestration, while SPG management lagged behind the others. Although both CG and PG management exhibited the same carbon sequestration rate, the carrying capacity (K value) was notably higher under PG management. This could account for the observed higher carbon stock in PG as compared to CG throughout the duration of the study. This data suggests a hierarchical efficiency in carbon sequestration by elm trees under different management practices: RG5 being the most efficient, followed by PG, CG, and then SPG.

Management practices can significantly shape vegetation carbon sequestration rates by influencing the structural and functional attributes of plant communities (Whittinghill et al., 2014). For instance, practices that promote plant diversity and maintain a dense vegetative cover tend to enhance the overall photosynthetic capacity of an ecosystem (Quijas et al., 2010). A diverse plant community, with species that have varied photosynthetic rates and growth patterns, can capture carbon more efficiently throughout the year (Zhang et al.,2016). Moreover, management interventions that optimize nutrient availability, such as controlled grazing or periodic soil amendments, can boost plant growth and thereby enhance their carbon intake (Ma et al., 2019).

Conversely, mismanaged practices can have deleterious effects on vegetation carbon sequestration. Overgrazing, for example, can result in the dominance of less productive plant species, diminishing the overall carbon capture capacity of the vegetation (Senbeta et al.,2013). Practices that lead to soil compaction or erosion can hinder root growth, thereby reducing the plant's ability to access water and nutrients essential for photosynthesis (Kim et al., 2010). Additionally, the loss or suppression of certain plant species due to specific management choices can disrupt the synchrony between plant phenology and climatic patterns, potentially leading to decreased photosynthetic periods (Pathare et al.,2017). Hence, tailoring management practices to the ecological needs of the vegetation is vital to maximize carbon sequestration rates.

Our findings, indicating carbon sequestration rates for elm trees ranging between 0.09 and 0.15 under various management measures, align with those reported by Bhatta et al. (2018) in Central Nepal. Bhatta and colleagues documented a carbon sequestration rate of 0.14 Mg C ha^{-1} $year^{-1}$ for trees within the Ulmaceae family. This further attests to the appropriateness of employing logistic models to capture the accumulation dynamics of biomass in vegetation. It's worth noting, however, that the carbon sequestration rates derived from our logistic models represent an average value across the entire life cycle of the vegetation and do not imply that the annual carbon sequestration rates for the plants consistently maintain this state.

4.3 Other factors influencing carbon stock in semi-arid lands

In addition to grazing management, the duration of grazing and grazing exclusion management can also influence carbon storage in soil and vegetation (Gebregergs et al.,2019). For example, ecosystem carbon storage in an alpine meadow steppe showed a hump-shaped pattern in response to the duration of grazing exclusion with a 6-year threshold (Li et al.,2018). In this study, the results provide evidence that the duration of grazing management influences vegetation carbon storage in sparse woodlands. Moreover, longer periods of grazing exclusion management do not necessarily lead to more vegetation carbon storage in over-mature trees. While our study emphasizes the importance of considering the duration of grazing management in decision-making processes to enhance carbon sequestration, it is pivotal to also scrutinize the specific strategies implemented during grazing. This encompasses analyzing the length and timing of rotations, as the efficacy of grazing management on carbon storage in sparse woodlands might be intricately linked to these variables. Moreover, integrating auxiliary strategies such as selective cutting, especially when trees exhibit diminished carbon storage capabilities, could serve as a pragmatic approach to sustain and potentially augment carbon sequestration in these ecosystems (Hulvey et al.,2013). Thus, a holistic approach, examining both the temporal and strategic facets of grazing management alongside supplementary woodland management practices like selective cutting, should be adopted to cultivate a robust framework that optimally supports carbon sequestration.

Climate changes, especially changes in precipitation and temperature, can affect vegetation carbon stock as biomass accumulation is influenced (Dai et al., 2013). Precipitation plays a vital role in regulating plant growth and vegetation patterns in terrestrial ecosystems (Peng et al.,2017). In sparse elm woodlands, population densities, but not the population age structure of elm trees, are greatly influenced by precipitation (Tang and Busso, 2018). The effects of precipitation on carbon storage in sparse elm woodlands are worth exploring in future research.

Livestock grazing can decrease the herb layer in terms of biomass, coverage, and spatial distribution (Eldridge et al., 2020; Trigo et al.,2020). Subsequently, the changes in herbs might affect the growth of elm trees, especially in the early stages of their life history. However, the effects of herbs on elm tree growth are relatively difficult to evaluate. Firstly, herbs play different roles in influencing the secondary dispersal of elm seeds. Herbs with vegetation coverage lower than the threshold can promote seed secondary dispersal, while herbs with vegetation coverage higher than the threshold can impede seed secondary dispersal (Jiang et al.,2014). Secondly, herbs have little effect on elm seed germination and seedling growth, as their effects might be mixed with other factors, such as light and litter biomass (Vaz et al., 2019). Thirdly, microbiomes might connect the interaction between herbs and elm trees, yet the role of microbiomes on plants in sparse elm woodlands is only recently being considered (Liang et al.,2019). Therefore, considering the interaction between herb layers and elm trees could promote the accuracy of tree growth models.

Conclusions

In our research, we crafted an advanced system dynamics model that integrates multiple life-history stages to explore the impact of livestock grazing management strategies on carbon storage, both in terms of carbon stock and sequestration rates. Importantly, for a nuanced estimation of carbon sequestration rates, we employed logistical models.

In this study, we examined four distinct grazing management strategies: RG5, PG, CG, and SPG. Our findings indicate that the carbon stock of elm trees under RG5 and PG management surpassed those observed under CG and SPG management. Moreover, our research highlights the differences in carbon sequestration rates of elm trees across these managements, with RG5 standing out as the most effective. As a result, our data suggests that rotational grazing management may offer a superior strategy to enhance vegetation carbon storage in sparse elm woodlands in semi-arid landscapes. Furthermore, in line with previous research, our logistic model outcomes showed that the carbon sequestration rates for elm trees ranged between 0.09 and 0.15 Mg C ha^{-1} $year^{-1}$.

Our assessment sheds light on the carbon sequestration capabilities of vegetation in sparse elm woodlands, offering valuable insights for grazing management in semi-arid regions. For a more refined understanding of carbon storage capacities in the future, it will be imperative to integrate soil carbon sequestration studies and delve deeper into the interactions between the herb layers and elm trees within these sparse woodlands.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (31870709) and the Scientific Research Funding Project of the Education Department of Liaoning Province (LJKZ0103).

References

Bayen, P., Noulekoun, F., Bognounou, F., Lykke, A.M., Djomo, A., Lamers, J.P.A., Thiombiano, A, 2020. Models for estimating aboveground biomass of four dryland woody species in Burkina Faso, West Africa. J Arid Environ. 180, 104205. doi:10.1016/j.jaridenv.2020.104205.

Bergmeier, E., Petermann, J., Schroeder, E., 2010. Geobotanical survey of wood-pasture habitats in Europe: diversity, threats and conservation. Biodivers. Conserv. 19, 2995-3014. doi:10.1007/s10531-010-9872-3.

Bhatta, S.P.; Sharma, K.P.; Balami, S. Variation in carbon storage among tree species in the planted forest of Kathmandu, Central Nepal. Curr. Sci. 2018, 115, 274–282.

Brown, H.C.A., Berninger, F.A., Larjavaara, M., Appiah, M., 2020. Above-ground carbon stocks and timber value of old timber plantations, secondary and primary forests in southern Ghana. Forest Ecol. Manage. 472, 118236. doi:10.1016/j.foreco.2020.118236.

Chang, X., Bao, X., Wang, S., Wilkes, A., Erdenetsetseg, B., Baival, B., Avaadorj, D.O., Maisaikhan, T., Damdinsuren, B., 2015. Simulating effects of grazing on soil organic carbon stocks in Mongolian grasslands. Agr. Ecosyst. Environ. 212, 278-284. doi:10.1016/j.agee.2015.07.014.

Chen, Y., Li, Y., Zhao, X., Awada, T., Shang, W., Han, J., 2012. Effects of Grazing Exclusion on Soil Properties and on Ecosystem Carbon and Nitrogen Storage in a Sandy Rangeland of Inner Mongolia, Northern China. Environ. Manage. 50, 622-632. doi:10.1007/s00267-012-9919-1.

Dai, L., Jia, J., Yu, D., Lewis, B.J., Zhou, L., Zhou, W., Zhao, W., Jiang, L., 2013. Effects of climate change on biomass carbon sequestration in old-growth forest ecosystems on Changbai Mountain in Northeast China. Forest Ecol. Manage. 300, 106-116. doi:10.1016/j.foreco.2012.06.046.

Dong, L., Bettinger, P., Liu, Z., 2021. Estimating the optimal internal carbon prices for balancing forest wood production and carbon sequestration: the case of northeast China. J. Clean. Prod. 281, 125342. https://doi.org/10.1016/j.jclepro.2020.125342.

Eldridge, D.J., Delgado-Baquerizo, M., 2017. Continental-scale Impacts of Livestock Grazing on Ecosystem Supporting and Regulating Services. Land Degrad. Dev. 28, 1473-1481, doi:10.1002/ldr.2668.

Eldridge, D.J., Oliver, I., Val, J., Travers, S.K., 2020. Limited evidence for the use of livestock for the conservation management of exotic plant cover. Aust. J. Bot. 68, 137-145. doi:10.1071/bt19183.

Farrell, K., Harpole, W., Stein, C., Suding, K., & Borer, E., 2015. Grassland Arthropods Are Controlled by Direct and Indirect Interactions with Cattle but Are Largely Unaffected by Plant Provenance. PLoS ONE, 10. https://doi.org/10.1371/journal.pone.0129823.

Fu, D.F., Bu, B., Wu, J.G., Singh, R.P.,2019. Investigation on the carbon sequestration capacity of vegetation along a heavy traffic load expressway. J. Environ. Manage. 241,549-557. doi:10.1016/j.jenvman.2018.09.098.
Gebregergs, T., Tessema, Z.K., Solomon, N., Birhane, E., 2019. Carbon sequestration and soil restoration potential of grazing lands under exclosure management in a semi-arid environment of northern Ethiopia. Ecol. Evol. 9, 6468-6479. doi:10.1002/ece3.5223.
Griffith, A.B., Forseth, I.N., 2005. Population matrix models of Aeschynomene virginica, a rare annual plant: Implications for conservation. Ecol. Appl. 15, 222-233. doi:10.1890/02-5219.
He, N.P., Zhang, Y.H., Yu, Q., Chen, Q.S., Pan, Q.M., Zhang, G.M., Han, X.G., 2011. Grazing intensity impacts soil carbon and nitrogen storage of continental steppe. Ecosphere 2(1):art 8. doi:10.1890/es10-00017.1.
He, N., Wen, D., Zhu, J., Tang, X., Xu, L., Zhang, L., Hu, H., Huang, M., Yu, G., 2017. Vegetation carbon sequestration in Chinese forests from 2010 to 2050. Global Change Biol. 23, 1575-1584. doi:10.1111/gcb.13479.
Hou, H.P., Zhang, S.L., Ding, Z.Y. , Huang, A.P., Tian, Y.F., 2015. Spatiotemporal dynamics of carbon storage in terrestrial ecosystem vegetation in the Xuzhou coal mining area, China. Environ. Earth Sci. 74(2):1657-1669.
Hulvey, K., Hobbs, R., Standish, R., Lindenmayer, D., Lach, L., & Perring, M., 2013. Benefits of tree mixes in carbon plantings. Nature Climate Change, 3, pp. 869-874.
Iglesias, M., Barchuk, A., Grilli, M. 2012. Carbon storage, community structure and canopy cover: A comparison along a precipitation gradient. Forest Ecol. Manage., 265, 218-229.
Jiang, D., Tang, Y., Busso, C.A., 2014.Effects of vegetation cover on recruitment of Ulmus pumila L. in Horqin Sandy Land, northeastern China. J. Arid Land 6, 343-351. doi:10.1007/s40333-013-0204-9.
Kim, H., Anderson, S., Motavalli, P., & Gantzer, C., 2010. Compaction effects on soil macropore geometry and related parameters for an arable field. Geoderma, 160, pp. 244-251. https://doi.org/10.1016/J.GEODERMA.2010.09.030.
Li, X., Ramos Aguila, L.C., Wu, D., Lie, Z., Xu, W., Tang, X., Liu, J. 2023. Carbon sequestration and storage capacity of Chinese fir at different stand ages. Sci Total Environ. 166962. doi: 10.1016/j.scitotenv.2023.166962.
Li, Y., Dong, S., Wen, L., Wang, X., Wu, Y., 2013. The effects of fencing on carbon stocks in the degraded alpine grasslands of the Qinghai-Tibetan Plateau. J. Environ. Manage. 128, 393-399. doi:10.1016/j.jenvman.2013.05.058.
Li, Y., Zhou, X., Brandle, J.R., Zhang, T., Chen, Y., Han, J., 2012. Temporal progress in improving carbon and nitrogen storage by grazing exclosure practice in a degraded land area of China's Horqin Sandy Grassland. Agr. Ecosyst. Environ. 159, 55-61. doi:10.1016/j.agee.2012.06.024.
Li, G.,2006. Biomass, Net Primary Productivity, and Ecological Restoration of Sparse Forest Grassland Ecosystem of Hunshandake Sandy Land. Graduate School of the Chinese Academy of Sciences, Beijing.
Li, W., Liu, Y., Wang, J., Shi, S., Cao, W., 2018. Six years of grazing exclusion is the optimum duration in the alpine meadow-steppe of the north-eastern Qinghai-Tibetan Plateau. Sci. Rep. 8, 17269. doi:10.1038/s41598-018-35273-y.
Liang, T., Yang, G., Ma, Y., Yao, Q., Ma, Y., Ma, H., Hu, Y., Yang, Y., Wang, S., Pan, Y., Li G.T., 2019. Seasonal dynamics of microbial diversity in the rhizosphere of Ulmus pumila

L. var. sabulosa in a steppe desert area of Northern China. Peerj 7, e7536. doi:10.7717/peerj.7526.
Liu, M., Tang, Y., 2018. The simulation in wind. driven seed dispersal of Ulmus pumila in sparse woodland steppe. Chin. J. Ecol. 37, 2524-2531. doi:10.13292/j.1000-4890.201808.001.
Lv, J., Chi, Y., Zhao, C., Zhang, Y., Mu, H., 2019. Experimental study of the supercritical CO_2 diffusion coefficient in porous media under reservoir conditions. Roy. Soc. Open Sci. 6, 181902. doi:10.1098/rsos.181902.
Marano, G., Collalti, A., 2020. Models of tree and stand dynamics: a differential journey through forest modelling. Iforest 13, 152-153. doi:10.3832/ifor0061-013.
Piao, S., Fang, J., Ciais, P., Peylin P., Huang, Y., Sitch, S., Wang, T., 2009. The carbon balance of terrestrial ecosystems in China. Nature 458, 1009–1013. https://doi.org/10.1038/nature07944
Ma, W., Li, J., Jimoh, S., Zhang, Y., Guo, F., Ding, Y., Li, X., & Hou, X., 2019. Stoichiometric ratios support plant adaption to grazing moderated by soil nutrients and root enzymes. PeerJ, 7. https://doi.org/10.7717/peerj.7047.
Medina-Roldan, E., Paz-Ferreiro, J., Bardgett, R.D., 2012. Grazing exclusion affects soil and plant communities, but has no impact on soil carbon storage in an upland grassland. Agr. Ecosyst. Environ. 149, 118-123. doi:10.1016/j.agee.2011.12.012.
Min, K., Choi, W., Kim, C., Choi, M., 2018. Oxidation-stable amine-containing adsorbents for carbon dioxide capture. Nat. Commun. 9, 726. doi:10.1038/s41467-018-03123-0.
Mukherjee, J., Ray, S., Ghosh, P.B., 2013. A system dynamic modeling of carbon cycle from mangrove litter to the adjacent Hooghly estuary, India. Ecol. Model. 252, 185-195. doi:10.1016/j.ecolmodel.2012.06.036.
Ngatia, L.W., Turner, B.L., Njoka, J.T., Young, T.P., Reddy, K.R., 2015. The effects of herbivory and nutrients on plant biomass and carbon storage in Vertisols of an East African savanna. Agr. Ecosyst. Environ. 208, 55-63. doi:10.1016/j.agee.2015.04.025.
Niu, H.,2008. Analiysis of population characterics of Ulmus pumila sparse forest in Hunshandake sandy land Inner Mongolia University, Hohhot.
Ouyang, Y., Xu, D., Leininger, T.D., Zhang, N., 2016.A system dynamic model to estimate hydrological processes and water use in a eucalypt plantation. Ecol. Eng. 6, 290-299. doi:10.1016/j.ecoleng.2015.11.008.
Pathare, V., Crous, K., Cooke, J., Creek, D., Ghannoum, O., & Ellsworth, D., 2017. Water availability affects seasonal CO2 ‐ induced photosynthetic enhancement in herbaceous species in a periodically dry woodland. Global Change Biology, 23, pp. 5164 - 5178. https://doi.org/10.1111/gcb.13778.
Peng, D., Zhang, B., Wu, C., Huete, A.R., Gonsamo, A., Lei, L., Ponce-Campos, G.E., Liu, X., Wu, Y., 2017. Country-level net primary production distribution and response to drought and land cover change. Sci. Total Environ. 574, 65-77. doi:10.1016/j.scitotenv.2016.09.033.
Piao, S., Huang, M., Liu, Z., Wang, X., Ciais, P., Canadell, J., Wang, K., Bastos, A., Friedlingstein, P., Houghton, R., Quéré, C., Liu, Y., Myneni, R., Peng, S., Pongratz, J., Sitch, S., Yan, T., Wang, Y., Zhu, Z., Wu, D., & Wang, T. 2018. Lower land-use emissions responsible for increased net land carbon sink during the slow warming period. Nature Geosci. 11, 739-743. https://doi.org/10.1038/s41561-018-0204-7.
Polley, H., Frank, A., Sanabria, J., & Phillips, R., 2008. Interannual variability in carbon dioxide

fluxes and flux‐climate relationships on grazed and ungrazed northern mixed‐grass prairie. Global Change Biology, 14. https://doi.org/10.1111/j.1365-2486.2008.01599.x.
Qiu, Z.X., Feng, Z.K., Song, Y.N., Li, M.L., Zhang, P.P., 2020. Carbon sequestration potential of forest vegetation in China from 2003 to 2050: Predicting forest vegetation growth based on climate and the environment. J. Clean. Prod. 252:119715.
Quijas, S., Schmid, B., & Balvanera, P., 2010. Plant diversity enhances provision of ecosystem services: A new synthesis. Basic and Applied Ecology, 11, pp. 582-593. https://doi.org/10.1016/J.BAAE.2010.06.009.
R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Ruhland, C.T., Niere, J.A., 2019. The effects of surface albedo and initial lignin concentration on photodegradation of two varieties of Sorghum bicolor litter. Sci. Rep. 9, 18748. doi:10.1038/s41598-019-55272-x.
Senbeta, F., Gole, T., Denich, M., & Kellbessa, E., 2013. Diversity of Useful Plants in the Coffee Forests of Ethiopia. Ethnobotany Research and Applications, 11, pp. 049-069.
Tang, Y., Jiang, D.M., Lv, X.T., 2014. Effects of Exclosure Management on Elm (Ulmus Pumila) Recruitment in Horqin Sandy Land, Northeastern China. Arid Land Res. Manage. 28, 109-117. doi:10.1080/15324982.2013.800922.
Tang, Y., 2020. Impact of grazing intensities on reproduction patterns of elm trees (Ulmus pumila) in degraded sandy lands in China. Peerj 8, e9013. doi:10.7717/peerj.9013.
Tang, Y., Li, X., 2018. Simulating effects of precipitation and initial planting density on population size of Mongolian pine in the Horqin Sandy Land, China. Agroforest. Syst. 92, 1-9. doi:10.1007/s10457-016-0004-2.
Tang, Y., Liu, M.Y., Wu, J.H., 2016. Effects of Thinning and Water Supply Manipulation on the Productivity of Pinus sylvestris var. mongolica in Northeastern China. Plos One 11, e0166109. doi:10.1371/journal.pone.0166109.
Tang, Y., Busso, C.A., 2018. Effects of precipitation changes on the dynamics of sparse elm woodland in Northeastern China. Biocell 42, 61-66. doi:10.32604/biocell.2018.07015.
Trigo, C.B., Villagra, P.E., Cowper Coles, P., Maras, G.A., Andrade-Diaz, M.S., Nunez-Regueiro, M.M., Derlindati, E.J., Talamo, A., 2020. Can livestock exclusion affect understory plant community structure? An experimental study in the dry Chaco forest, Argentina. Forest Ecol. Manage. 463, 6324. doi:10.1016/j.foreco.2020.118014.
Trilleras, J.M., Jaramillo, V.J., Vega, E.V., Balvanera, P., 2015. Effects of livestock management on the supply of ecosystem services in pastures in a tropical dry region of western Mexico. Agr. Ecosyst. Environ. 211, 133-144. doi:10.1016/j.agee.2015.06.011.
Vaz, P.G., Bugalho, M.N., Fedriani, J.M., Branco, M., Lecomte, X., Nogueira, C., Caldeira, M.C., 2019. Unravelling associations between tree-seedling performance, herbivory, competition, and facilitation in high nature value farmlands. J. Environ. Manage. 232, 1066-1074. doi:10.1016/j.jenvman.2018.11.082.
Wang, L., Gan, Y., Wiesmeier, M., Zhao, G., Zhang, R., Han, G., Siddique, K.H.M., Hou, F., 2018. Grazing exclusion-An effective approach for naturally restoring degraded grasslands in Northern China. Land Degrad. Dev. 29, 4439-4456. doi:10.1002/ldr.3191.
Wang, D., Wang, B., Niu, X., 2014. Forest carbon sequestration in China and its benefits. Scand. J. Forest Res. 29, 51-59. doi:10.1080/02827581.2013.856936.
Whittinghill, L., Rowe, D., Schutzki, R., & Cregg, B., 2014. Quantifying carbon sequestration of various green roof and ornamental landscape systems. Landscape and Urban Planning,

123, pp. 41-48.
Wu, X., Li, Z., Fu, B., Lu, F., Wang, D., Liu, H., Liu, G., 2014. Effects of grazing exclusion on soil carbon and nitrogen storage in semi-arid grassland in Inner Mongolia, China. Chin. Geogr. Sci. 24, 479-487.doi:10.1007/s11769-014-0694-1.
Xiong, D., Shi, P., Zhang, X., Zou, C.B., 2016. Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China A meta-analysis. Ecol. Eng.94, 647-655. doi:10.1016/j.ecoleng.2016.06.124.
Yang, J., Tang, Y., 2019. The increase in ecosystem services values of the sand dune succession in northeastern China. Heliyon 5, e02243. doi:10.1016/j.heliyon.2019.e02243.
Zellweger, F., Flack-Prain, S., Footring, J., Wilebore, B., Willis, K.J., 2022. Carbon storage and sequestration rates of trees inside and outside forests in Great Britain. Environ. Res. Lett.17(7): 074004.
Zhang, A., Fan, D., Li, Z., Xiong, G., & Xie, Z., 2016. Enhanced photosynthetic capacity by perennials in the riparian zone of the Three Gorges Reservoir Area, China. Ecological Engineering, 90, pp. 6-11. https://doi.org/10.1016/J.ECOLENG.2016.01.075.
Zhang, C., Dong, Q., Chu, H., Shi, J., Li, S., Wang, Y., & Yang, X., 2017. Grassland Community Composition Response to Grazing Intensity Under Different Grazing Regimes. Rangeland Ecology and Management, 71, pp. 196 - 204.
Zhang, X., Zhang, F., Kung, H.T., Shi, P., Ayinuer, Y., Zhu, S., 2018. Estimation of the Fe and Cu Contents of the Surface Water in the Ebinur Lake Basin Based on LIBS and a Machine Learning Algorithm. Int. J. Environ. Res. Public Health 15(11), 2390. doi:10.3390/ijerph15112390.
Zhang, M., Wu, J., Tang, Y., 2016. The effects of grazing on the spatial pattern of elm (*Ulmus pumila* L.) in the sparse woodland steppe of Horqin Sandy Land in northeastern China. Solid Earth 7, 631-637. doi:10.5194/se-7-631-2016.
Zhao, W., Hu, Z.M., Yang, H., Zhang, L.M., Guo, Q., Wu, Z.Y., Liu, D.Y., Li, S.G., 2016. Carbon density characteristics of sparse Ulmus pumila forest and Populus simonii plantation in Onqin Daga Sandy Land and their relationships with stand age. Chin. J. Plant Ecol. 40, 318-326. doi:10.17521/cjpe.2015.1080.

Figure 1

Figure1. Carbon stock in U. pumila of sparse woodlands under livestock grazing management

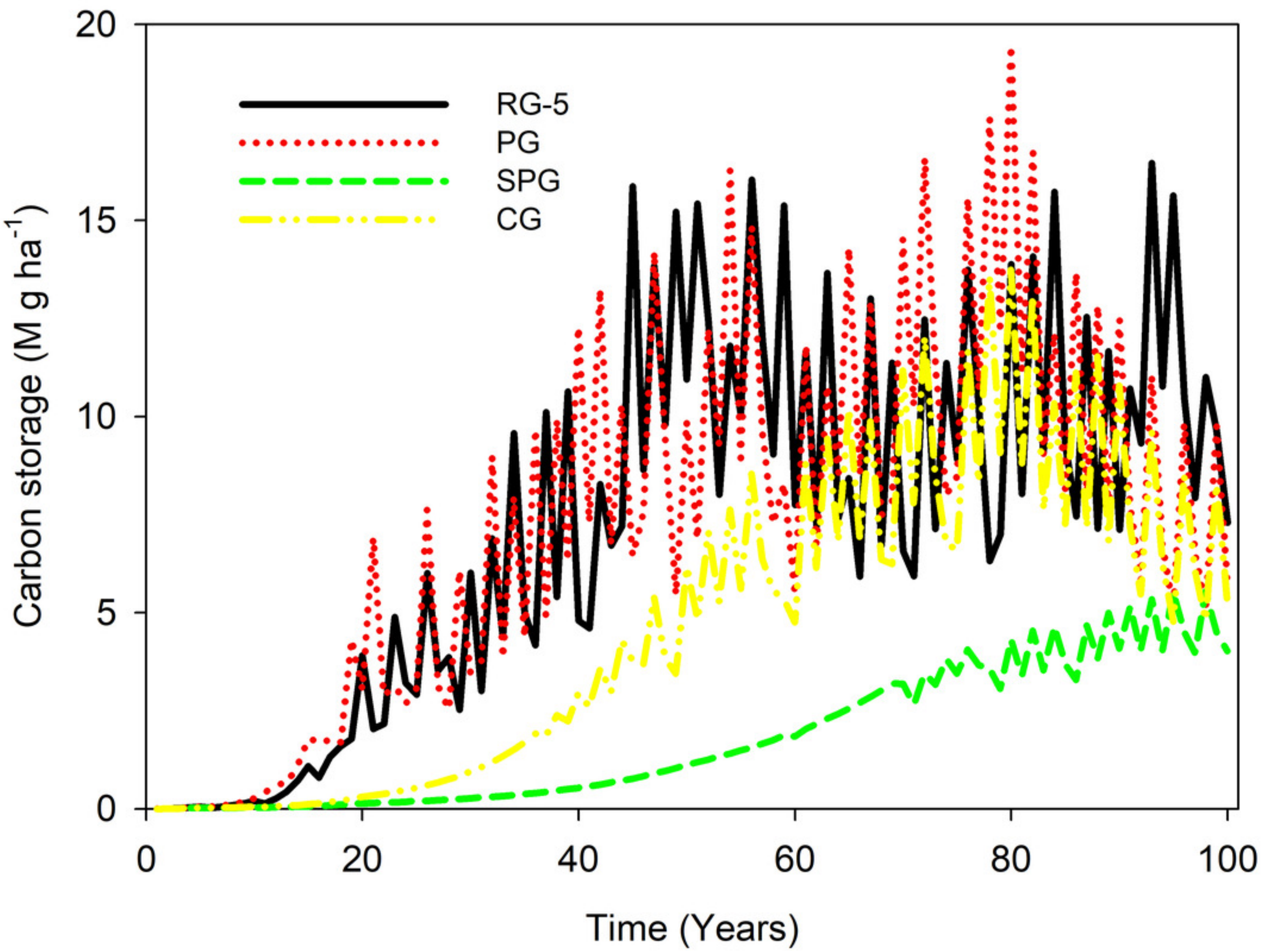

Figure 2

Figure 2. Simulation results of Carbon stock were fitted with logistical models

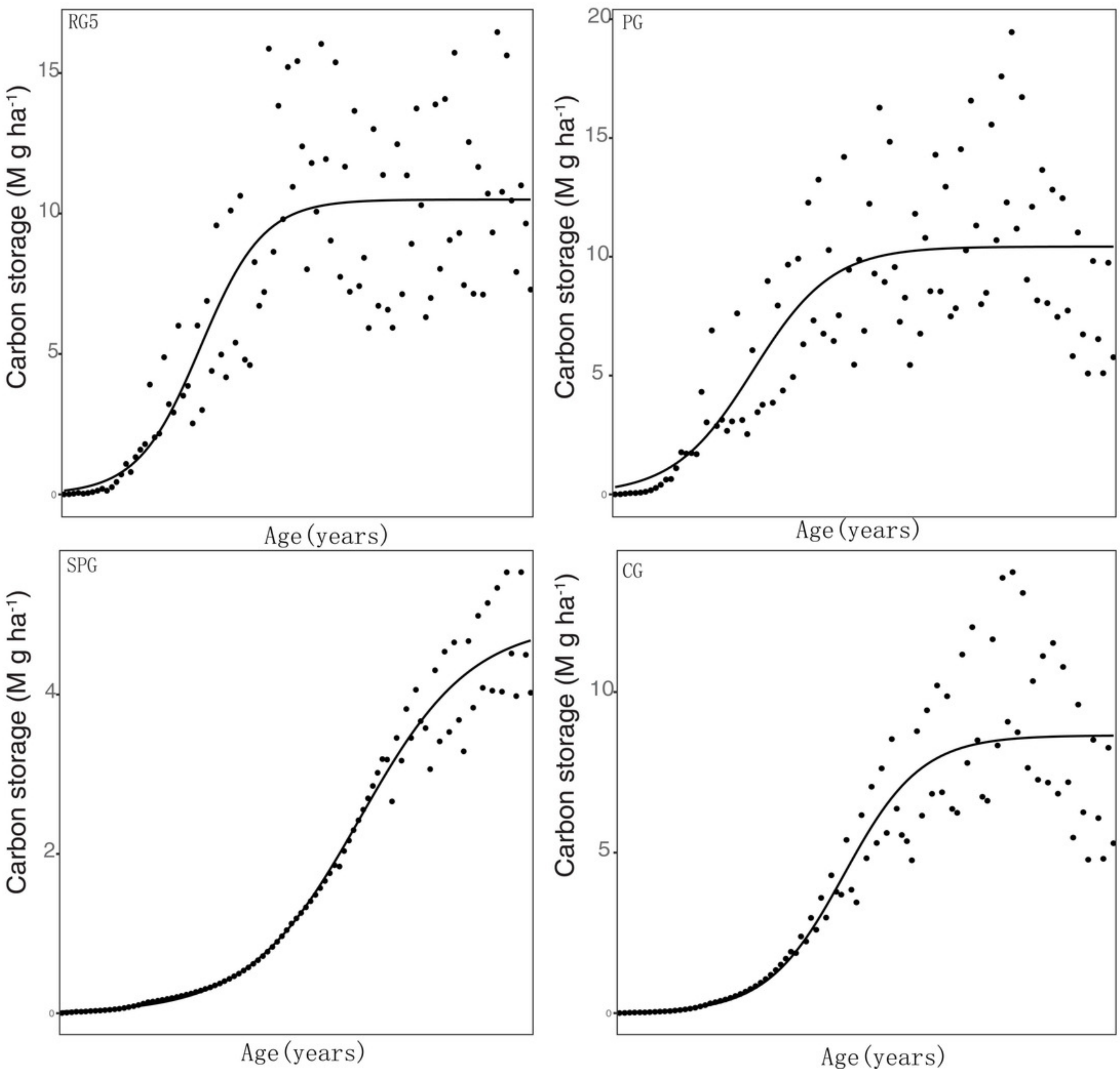

Table 1 (on next page)

Values of parameters used in the system dynamic model

1 **Table 1** Values of parameters used in the system dynamic model

Parameters	Seed	Seedling	Juvenile tree	Mature tree	Over-mature tree
seed production(seeds·m^{-2})	-	-	-	2456	7744
Death rate(%)	-	0.268	0.133	0.346	0.941
Expectation in precipitation(mm)	352	352	352	352	352
Variance in precipitation	8627	8627	8627	8627	8627
Seed germinatied rate(%)	-	-	-	10	10
Period of stages (years)	1	5	15	30	50
Transition probability(%)	-	20	6.67	3.33	2
Water consumption (L/individuals year)	-	21.6	1680.7	1977	1977
RG5	1.51	0.56	0.89	-	-
CG	1.51	0.56	0.89	-	-
SPG	-	0.56	0.89	-	-

2

Table 2(on next page)

The values of parameters describing the allometric growth and carbon contents of leaf, twig, stem, and root in elm trees

Table 2 The values of parameters describing the allometric growth and carbon contents of leaf, twig, stem, and root in elm trees

Parameters	Leaf	Swig	Stem	Root
a	0.033	0.0303	0.0146	0.0146
b	1.7241	2.3445	2.5837	2.893
C content(g Kg^{-1})	406	444	446	424

Table 3 (on next page)

The values of estimated parameters in logistical models of Carbon stock

Table 3. The values of estimated parameters in logistical models of Carbon stock

Scenarios	K		N_0		R_{seq}		RSE
	Mean	SE	Mean	SE	Mean	SE	
RG5	10.5	0.39	0.1	0.11	0.15	0.03	2.635
PG	10.43	0.45	0.24	0.21	0.13	0.03	2.914
SPG	4.9	0.15	0.02	0.01	0.09	0.01	0.3071
CG	8.65	0.32	0.02	0.02	0.13	0.02	1.648

The bold letters indicate that the corresponding parameters are significant at the 0.05 level.