Carbon stocks of sparse forests are regulated by the livestock grazing management in 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 in RG5, PG, CG, and SPG management, respectively. This indicates that rotational grazing and prohibited grazing management performed well in increasing vegetation carbon storage. Therefore, rotational grazing and prohibited grazing management might be the optimal choice for improving vegetation carbon accumulation in sparse woodlands. Additionally, we found that the system dynamic approach is an effective method for evaluating vegetation carbon stock, and that logistical models should be used instead of linear models to evaluate the carbon sequestration rate in vegetation. 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 in RG5, PG, CG, and SPG management, respectively. This indicates that rotational grazing and prohibited grazing management performed well in increasing vegetation carbon storage. Therefore, rotational grazing and prohibited grazing management might be the optimal choice for improving vegetation carbon accumulation in sparse woodlands. Additionally, we found that the system dynamic approach is an effective method for evaluating vegetation carbon stock, and that logistical models should be used instead of linear models to evaluate the carbon sequestration rate in vegetation. This study contributes to decision-making on how to choose livestock grazing management to maintain higher carbon storage.

Keywords: biomass; elm trees; logistic model; system dynamic approach

Introduction

Global warming, which is primarily caused by excessive emissions of CO2, has attracted worldwide attention (Lv et al.,2019). One important strategy for reducing anthropogenic CO2 emissions is carbon storage (Min et al.,2018). The terrestrial biosphere, which holds 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). In addition to storing carbon, vegetation also plays a crucial role in regulating the carbon cycle by absorbing CO2 through photosynthesis and releasing it through respiration (Qiu et al, 2020). Therefore, increasing vegetation carbon storage is an effective way to mitigate global warming.

Arid and semi-arid areas together constitute almost one-third of the world's land area (Zhang et al.,2018). In these areas, livestock grazing is a significant type of 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).

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.

The model simulation approach can consider the effects of various types of livestock grazing management on a common baseline and make full 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).

A concise result of comparing the effects of grazing management on vegetation carbon storage has benefits in guiding policy decisions for livestock grazing management and in evaluating ecosystem services. Firstly, maintaining more carbon storage in ecosystems can reduce atmospheric CO2 emissions and, in turn, alleviate global warming (Piao et al., 2009). Therefore, management practices that maintain more vegetation carbon storage are preferred. Additionally, remaining carbon stock is a vital component of ecosystem services (Yang and Tang, 2019). Grazing management can influence ecological services by regulating carbon stock in ecosystems. Therefore, grazing management is an important aspect in deploying ecological services.

Carbon sequestration rates are used to estimate the change in carbon input to the soil by calculating the carbon storage under the initial and alternative practices (West and Post, 2002). The carbon sequestration rates are also used to calculate and compare the carbon storage in forests at large scales (Wang et al.,2014; He et al.,2017). The equations to calculate the vegetation carbon sequestration rates are linear models, which assume that the accumulation in carbon storage is linear growth. However, as the accumulation in vegetation carbon storage follows the growth of plants, i.e., logistical growth mostly, more accurate models might be needed.

The main aim of this study was to 1) compare the effects of livestock grazing management on carbon stock in sparse woodlands in semi-arid lands, and 2) provide a model to estimate the C sequestration rate in vegetation. The contribution of this study is that: 1) comparing the difference in vegetation carbon storage under various livestock grazing management practices could help make more informed policy decisions to promote carbon storage in vegetation; 2) a more accurate model for calculating the C sequestration rate in vegetation is useful for evaluating the efficiency of carbon storage.

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).

A system dynamic model was built considering 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.

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

$$\frac{dN_i}{dt} = \left\{ \begin{matrix} TP_{i-1} \cdot N_{i-1} - (D_i + TP_i) \cdot N_i, N_i < Max_i \\ 0 \qquad ,N_i \geq Max_i \end{matrix} \right\}, i = 2, \cdots, n-1 \qquad (2)$$

$$\frac{dN_i}{dt} = \left\{ \begin{matrix} TP_{i-1} \cdot N_{i-1} - D_i \cdot N_i,\ N_i < Max \\ 0 \qquad ,N_i \geq Max \end{matrix} \right\} \cdots\cdots\cdots\cdots i = n \qquad (3)$$

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

Where N represents the number of individuals at each of the five stages, B and D represent the birth and death rates, and TP represents 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

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.

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

In equation 5, i ranges from 1 to 4, representing the leaf, twig, stem, and root separately. The C content 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 ai and bi are special parameters measured in a previous study (Li, 2006), i from 1 to 4 representing leaf, twig, stem, and root separately (Table 2). The DBH was estimated with equation 7, where the age of elm tree serves as an independent variable.

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

Where A and B are estimated using data from a previous study; here, DBH and age of elm trees are reported(Niu, 2008). The vegetation C sequestration rate was obtained with a logistic model, where the C sequestration rate (Rseq) serves as a parameter and is estimated using equation 8.

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

where K, and N_0 are parameters. Carbon stock and age of elm trees are the response and predictor variables, respectively.

Table 2 is here

The 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).

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.

The estimated linear models in equations 7 and 8 were calculated using R programming language (R Core Team, 2022). The fittest model in 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 more extensive 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. 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 fell within the range of 10 M g ha^{-1} to 15 M g ha^{-1} after the 40th year under RG5 and PG management (Figure 1).

3.2. The C sequestration rate of elm trees

The rate of carbon sequestration 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 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

In RG5 and PG management, the accumulation of 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 sample densities were found to be significantly higher in fenced plots than in grazed plots (Tang et al.,2014). This might be 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 value of the carbon sequestration rate was the highest in PG5 management and the lowest in SPG management. Although the value of the carbon sequestration rate was the same in CG and PG management, the K value was more extensive in PG management than in CG management. This suggests that the ability to sequester carbon in elm trees is ordered as follows: PG5, PG, CG, and SPG management. In this study, the carbon sequestration rate was calculated using logistic models. Logistic models can reflect the accumulation of biomass in vegetation, making them better suited for evaluating the carbon sequestration rate than linear models. It is suggested that the carbon sequestration rate of vegetation, especially plant populations, should be evaluated using logistic models instead of linear models.

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.

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. This suggests that the duration of grazing management should be taken into consideration during decision making to improve 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

Rotational grazing and prohibited grazing management perform well in increasing vegetation carbon storage in sparse woodlands. Rotational grazing and prohibited grazing management might be the optimal choice for improving vegetation carbon accumulation in semi-arid lands. Furthermore, this study suggests that the system dynamic approach is an effective method for evaluating vegetation carbon stock. Additionally, it is recommended that logistical models should be used instead of linear models to evaluate the carbon sequestration rate in vegetation.

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Figure 1

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

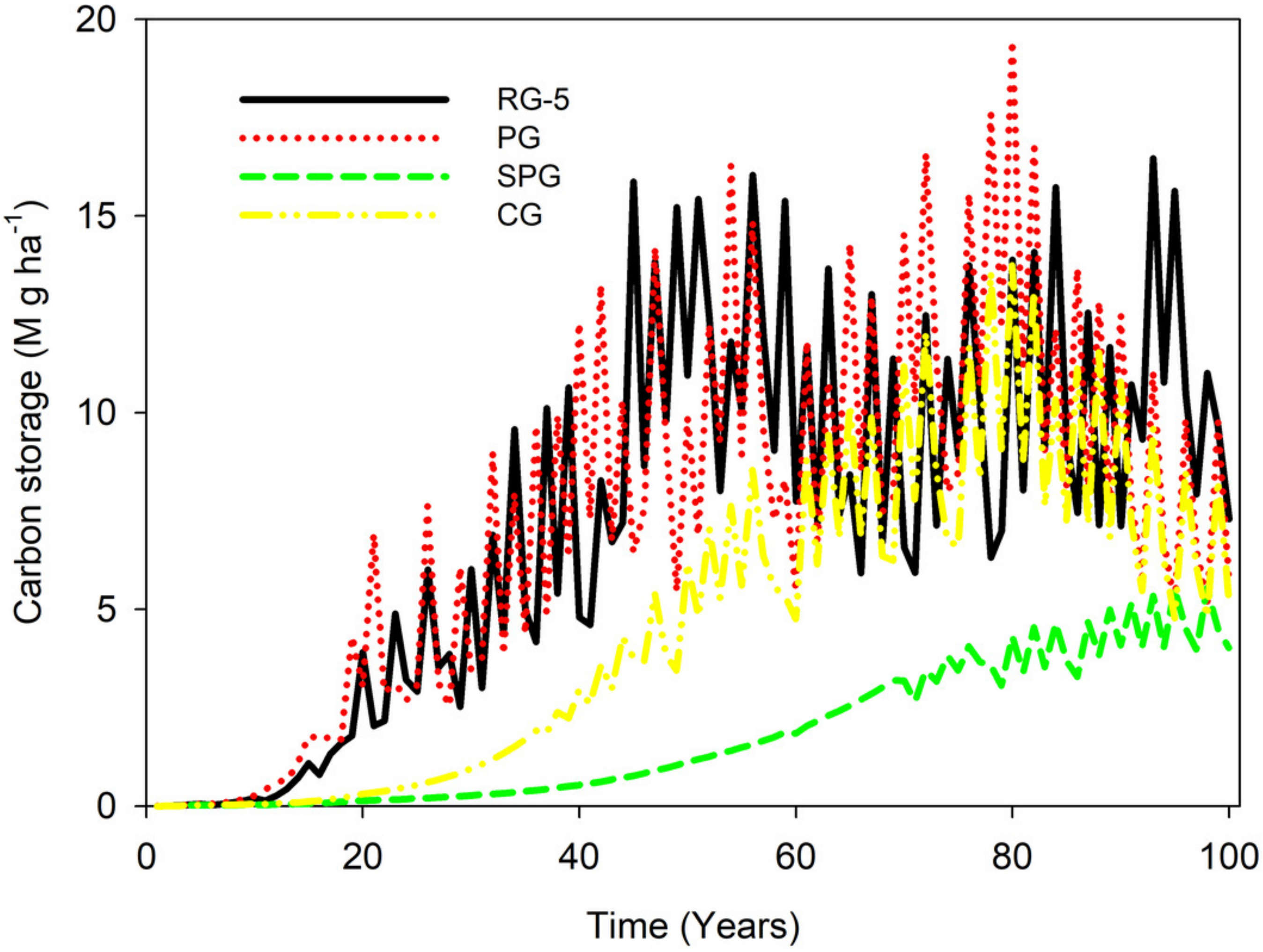

Figure 2

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

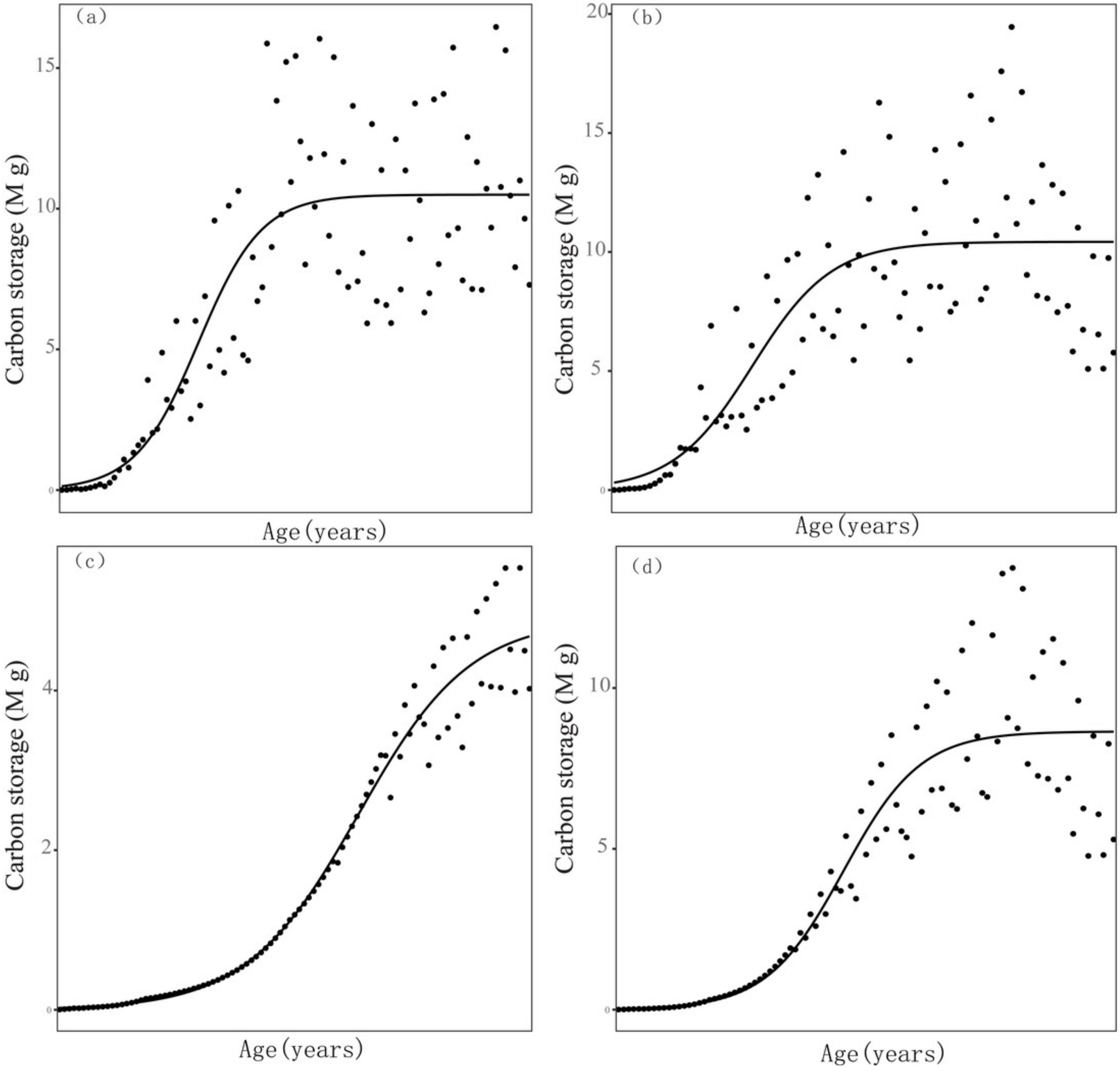

Table 1(on next page)

Values of parameters used in the system dynamic model

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	-	-

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.