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Original Research

Effects of Grazing on Population Growth Characteristics of *Caragana stenophylla* Along a Climatic Aridity Gradient[☆]

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ABSTRACT

Shrubs are important plant species in grassland ecosystems worldwide, and their density and cover have been gradually increasing globally. However, the interaction effect of grazing and aridity on population recruitment and population growth of shrub species in grasslands has not been examined explicitly. We examined sapling establishment, sexual recruitment, population mortality, and population growth of *Caragana stenophylla* along a climatic aridity gradient and a grazing intensity gradient in the Inner Mongolia Steppe, using manipulative field experiments. Sapling establishment, sapling height, and sexual recruitment of *C. stenophylla* decreased as climatic aridity and grazing intensity increased. The negative effects of grazing on sapling establishment and sexual recruitment gradually increased as climatic aridity increased. The effect of climatic aridity and grazing on population mortality was influenced by sexual recruitment. In the combined treatments of climatic aridity and grazing, population mortality was relatively high when sexual recruitment was relatively high, while population mortality increased as climatic aridity and grazing increased when sexual recruitment was relatively low. *C. stenophylla* population increased under relatively low drought stress and mild grazing but declined under strong drought stress and/or severe grazing. Our results suggested that to maintain viable *Caragana* populations, appropriate grazing policies must be made according to climate aridity gradient.

Introduction

Population growth is basically determined by recruitment and mortality (Li et al., 2013). Sapling establishment is a critical step for recruitment because of the relatively high mortality rate during this stage. Sapling establishment is affected by biotic factors, such as seed addition (Moles and Westoby, 2002), interspecific competition (Carón et al., 2015b), below-ground competition (Haugo et al., 2013), plant size (Li et al., 2013), clonal integration (Yu et al., 2004), interspecific facilitation (Holl, 2002; Castro et al., 2004b; Caldeira et al., 2014), and grazing (Buckley et al., 2010; Osem et al., 2015). Sapling establishment is also affected by abiotic factors, such as soil origin (prairie vs. forest) (Haugo et al., 2013), sand burial (Zhao et al., 2007; Li et al., 2010), denudation (Li et al., 2010), drought (Noumi et al., 2015; Carón et al., 2015a), and precipitation (Carón et al., 2015b). The mortality rate is also influenced by biotic factors and abiotic factors, such as interspecific competition (Ehrlén et al., 2005; Hamre et al., 2010), grazing (Hunt, 2010), drought (Faust et al., 2011), soil nutrients and water availability (de Campos Franci et al., 2016), sand burial (Li et al., 2010), and precipitation and soil sand content (Fortunel et al., 2016).

Climatic aridity and grazing are two widespread, often co-occurring factors affecting sapling establishment, population mortality, and population growth of plant species in the Inner Mongolia Steppe (Fynn and O'Connor, 2000; Chen and Tang, 2005). Previous studies in other areas showed that drought severely limited regeneration of trees and increased population mortality rate (Traveset et al., 2003; Castro et al., 2004a, 2005). But how sapling recruitment and the consequent population growth changes along a climatic aridity gradient remain unclear (Cipriotti et al., 2008). Grazing can influence plant recruitment by decreasing seedling numbers (Macias et al., 2014; Smit et al., 2015), restraining seedling height (Osem et al., 2015), and increasing seedling mortality rate. Therefore, grazing has negative effects on population growth (Farrington et al., 2009; Hegland et al., 2010; Mandle and Ticktin, 2012; Mandle et al., 2015). However, few studies explicitly examined the combined effects of climatic aridity and grazing on the population growth (Hunt, 2010; Faust et al., 2011). Understanding the combined effects of climatic aridity and grazing on the population growth of plant species is critical for appropriate grazing management of grasslands under different climatic regimes.

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Shrubs are important plant species in grassland ecosystems worldwide, and their density and cover have been gradually increasing globally. *Caragana* species are widespread and dominant shrub species in the Inner Mongolia Steppe, China (Xiong et al., 2002). In grasslands, *Caragana* species have not only economic values as important fodder, green manure, and honey resource but also environmental protection values for wind-erosion attenuation, sand fixation, and water and soil conservation. *Caragana* species play increasingly important roles in mediating grassland ecosystem functions and services. Therefore, understanding the population growth characteristics of *Caragana* species was critical for maintaining the sustainability of grassland ecosystem functions and services.

There are 16 *Caragana* species distributed in the Inner Mongolia Steppe, and *Caragana stenophylla* is one of the most important plant species with its widespread distribution, forage value, and other ecological functions in the region (Xie et al., 2014). Therefore, we selected *C. stenophylla* as the target plant species to examine the population growth characteristics of *Caragana* species under the combined influences of climatic aridity and grazing gradients in the Inner Mongolia Steppe.

Seed production and seedling establishment are two critical processes of sexual recruitment for plant populations. We previously reported the seed production characteristics of *C. stenophylla* under the combined influences of climatic aridity and grazing gradients in the Inner Mongolia Steppe (Xie et al., 2016). In this study, we examined the sapling establishment of *C. stenophylla* along a climatic aridity gradient (across semiarid, arid, very arid, and intensively arid zones) and a grazing intensity gradient (fenced, mildly and severely grazed) using manipulative field experiments in the Inner Mongolia Steppe. Moreover, we calculated the annual sexual recruitment (the annual number of saplings produced by each plant) of *C. stenophylla* based on annual seed production (Xie et al., 2016) and sapling establishment rate. Meanwhile, we investigated the annual population mortality along this climate gradient and grazing intensity using population demography. On the basis of the annual sexual recruitment and annual population mortality, we quantified the annual population growth of *C. stenophylla*. We aimed to answer the following questions: 1) What are the effects of the interactions between climatic aridity and grazing on the sapling establishment of *C. stenophylla*, and 2) What are the combined effects of climatic aridity and grazing on the population growth of *C. stenophylla?* Our study provides the scientific basis for appropriate grazing management along climatic aridity gradients in grassland ecosystems.

Methods

Study Sites and Study Material

The Inner Mongolia Steppe, located in the northern China, spans an extensive area (~1183×10^3 km^2), ranging from 97°12′E to 126°04′E in longitude (a distance of ~2 500 km) and 37°24′N to 53°23′N in latitude (a distance of ~1 700 km), and is one of the largest steppes in the world. There is a strong gradient of increasing climatic aridity from the northeast to the southwest (across humid, subhumid, semiarid, arid, very arid, intensively arid, and extremely arid zones). Grazing by livestock is a common land use form in the Inner Mongolia Steppe. Therefore, the Inner Mongolia Steppe provides an ideal system to study plant population growth under combined influences of climatic aridity gradient and grazing.

C. stenophylla is a leguminous, xeromorphic, deciduous dwarf-shrub with a spinose stem, which is distributed across a large geographic range in the Inner Mongolia Steppe, predominately from the semiarid zone to the intensively arid zone (Ma et al., 2013; Xie et al., 2015). *C. stenophylla* has both sexual and clonal reproduction.

Experimental Design

We conducted the field study at 4 sites: 1) Xilinhaote in the semiarid zone, 2) Siziwang in the arid zone, 3) Etuoke in the very arid zone, and 4) Alashanzuo in the intensively arid zone of the Inner Mongolia Steppe. Geographical locations and environmental data of these study sites are shown in Figure 1 and Table 1**.**

At each study site, we selected three plots for fenced, mildly grazed and severely grazed management. And each plot was more than 500 ha. Within each plot, we demarcated four subplots (~3 ha each subplot) with distances of ~800 m between subplots. Because vegetation coverage decreased gradually as the climatic drought stress increased from the semiarid zone to the intensively arid zone, the grazing intensity was set according to local vegetation conditions for logistic reasons. At each study site, the grazing intensity in the severely grazed plot was about twice as high as that in the mildly grazed plot. The grazing intensity at each study site was mildly grazed, Xilinhaote (in the semiarid zone) 1.2 sheep per ha; Siziwang (in the arid zone) 1.0 sheep per ha; Etuoke (in the very arid zone) 0.8 sheep per ha; Alashanzuo (in the intensively arid zone) 0.4 sheep per ha; severely grazed, Xilinhaote 2.8 sheep per ha, Siziwang 1.9 sheep per ha; Etuoke1.5 sheep per ha; and Alashanzuo 0.8 sheep per ha. The grazing treatments at each study site have been established for > 5 yr.

Seed Vigor Measurements

During June − July in 2012 and 2013, we collected and air-dried healthy *C. stenophylla* seeds from each of four study sites, respectively. We put the seeds in the field for the winter and measured seed vigor in the next March. We did not consider the effect of grazing intensities on seed vigor measurements because there were very few or no seeds in the severely grazed plots (Xie et al., 2016); thus, we did not include the factor of grazing intensity when collecting seeds from each aridity zone. Germination rate and germination index values (averages) were calculated on 2 yr of germination data. Germination rate and germination index were calculated using following formulas:

$$\text{Germination rate} = (\text{the number of germinated seeds}/\text{the total number of experimental seeds}) \times 100\%$$

$$\text{Germination index} = \sum \text{Gt}/\text{Dt}\ (\text{Gt represents the number of germinated seeds on day t, Dt represents corresponding germination days})$$

Seedling or Sapling Establishment

The twice − field-sowing experiments were conducted during 2013 − 2014 and 2014 − 2015, respectively. At the beginning of the growing season in 2013 and 2014, we sowed *C. stenophylla* seeds within plots. The seeds sowed to each site were collected from the same site in the previous year. The beginning time of growing season varies among the four study sites, so we sowed the seeds on different dates at different sites according to the timing of the local growing season. Sowing dates were April 20 at Alashanzuo site, April 26 at Etuoke site, May 1 at Siziwang site, and May 8 at Xilinhaote site.

In each subplot, we established two transects of 90 m in each subplot and placed 1 × 1 m quadrats at intervals of 10 m along each transect (in total 18 quadrats per subplot), and the quadrats were under/in *C. stenophylla* shrubs, grasses, or open areas. We sowed 100 seeds in each quadrat (1 800 seeds per subplot, 7 200 seeds per plot, and in total 21 600 seeds per site). Our previous study has investigated the seed densities of *C. stenophylla* in soils (semiarid zone: 4 seeds/m^2; arid zone: 2 seed/m^2; very arid zone: 1 seed/m^2; intensively arid zone: 0.5 seed/m^2) (Xie et al., 2015). Thus, when sowing seeds, we deducted the number of preexisting seeds in soil. Six mo after sowing (at the end of the growing season in current year) and 18 mo after sowing (at the end of the growing season in the next year), we recorded seedling (6 mo old) or sapling (18 mo old) number in each quadrat and then calculated seedling or sapling establishment rate for each quadrat (18 quadrats per subplot) using the following formula: seedling or sapling establishment rate = seedling

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