

Effects of precipitation changes on the dynamics of sparse elm woodland in Northeastern China

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Key words: Population density, Precipitation, Semi-arid lands, System dynamics model

Abstract: Elm (*Ulmus pumila* L.) is the dominant tree species in the sparse elm woodland, the original vegetation in the Horqin Sandy Land. The effects of changes in precipitation on *U. pumila* trees have not been fully studied. We determined a dynamic model by considering the five stages in the *U. pumila* life cycle, *i.e.* seed, seedling, and juvenile, mature and over-mature tree stages. The effects of changes in precipitation on population density and age structure were then evaluated. Population density, after averaging all study developmental morphology stages, ranged from 16.67 individuals/m² to 25.01 individuals/m² under a mean annual precipitation (MAP) of 80% to 120%, respectively. This suggests that population density could increase as MAP also increased. The proportion of seedlings, and juvenile, mature and over-mature trees were 95.23%, 4.58%, 0.19% and 0.01%, respectively, under all precipitation levels. This indicates that precipitation had little effects on the developmental stages of the studied *U. pumila* populations in the Horqin Sandy Land. Additional water supply might be provided in addition to the natural rainfall that occurs in the region, for contributing to maintain *U. pumila* population density in the Horqin Sandy Land.

Introduction

Changes in precipitation are one of the most important aspects of climate change, which is mainly caused by global warming (Brewer, 1994). Changes in climate might lead to a reduction in precipitation and an increased intensity of drought in arid lands (Dore, 2005; Trenberth *et al.*, 2014). In arid and semi-arid lands, drought is one of the most important factors that limit plant development (Klausmeier, 1999). Changes in precipitation are a key factor in the regulation of plant population development, especially in arid and semi-arid environments (Giorgetti *et al.*, 1997; Miao *et al.*, 2018). They have changed land use on many regions in the world with negative results on the renewable natural resources (*i.e.* increased land degradation). For example, land used previously for meat production on native rangelands is currently used for crop production in arid and semiarid territories (Busso and Fernández, *in press*). These changes in land utilization because of precipitation changes had negative social and economic consequences in arid and semiarid zones of the world (Busso and Fernández, *in press*).

The effects of changes in precipitation on plants have been investigated by studying various morphophysiological plant traits (Busso *et al.*, 2003; Bonvissuto and Basso, 2007; Piao

et al., 2012; Albert *et al.*, 2013; Claesson and Nycander, 2013). Recently, some reports have focused on the effects that changes in precipitation might have on plant population dynamics (Dalglish *et al.*, 2011, Martin and Meinke, 2012; Prevey and Seastedt, 2015). This is crucial to understand the interaction between plants and their environments, and for exploring the mechanisms regulating the temporal-spatial formation of plant populations, especially in arid and semi-arid lands, where precipitation is the main source of water supply (Benavides *et al.*, 2016).

Ulmus pumila, a tree species, is dominant in sparse elm woodland, which is the original vegetation in the Horqin Sandy Land, one of the largest sandy lands in China (Jiang *et al.*, 2014). Maintenance of sparse elm woodland is critical for vegetation restoration in the Horqin Sandy Land, where rehabilitation with native species has become a useful way to control desertification (Normile, 2007). Thus, exploring the effects of precipitation on the dynamics of *U. pumila* populations might help us to understand the stability of sparse elm woodland, and promote the restoration of vegetation in the Horqin Sandy Land.

The effects of precipitation on *U. pumila* trees in sparse elm woodland have been studied (Dulamsuren *et al.*, 2009b). However, the effects on *U. pumila* trees caused by changes in precipitation are not fully understood. This might lead to an inaccurate assessment of the status of the *U. pumila* population, especially when considering the background of climate changes. Therefore, it is critical to explore the effects of different

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precipitation levels on population dynamic of *U. pumila*.

The simulation methods have proved to be a feasible tool to look at the scenarios of plant populations under different environmental conditions (Tang *et al.*, 2015). For example, effects of the timing of flooding recession and precipitation were evaluated with deterministic and stochastic matrix population models on the population dynamic of *Boltonia decurrens* (Smith *et al.*, 2005). In addition, the effects of different fire frequencies, and variations in spring precipitation levels, were studied with stochastic models on the population dynamic of *Fabiana imbricate* (Curth *et al.*, 2012).

The aim of this work was to understand how various precipitation levels influence the population dynamic (e.g. population density and age structure) of *U. pumila* trees in sparse elm woodland. With this purpose, we constructed a systematical dynamic (SD) model, where population dynamic was structured at five morphological stages of development: seed, seedling, and juvenile, mature and over-mature trees. We used various parameters based on field studies as input variables to feed the model at the studied developmental stages. The stochastic precipitation was considered a key factor for regulating growth of the *U. pumila* population.

Materials and Methods

Model construction

We established a dynamic model considering the five stages of the *U. pumila* life cycle, *i.e.* seed ($i=1$), seedling, juvenile, mature and over-mature ($i=5$) tree stages (Fig. 1). The model was established following the equations below where at the seed stage i was from 4 to 5.

$$\left\{ \begin{array}{l} \frac{dN_i}{dt} = \sum_{i=4}^5 B_i \cdot N_i - TP_i \dots\dots\dots \text{for seed stage} \\ \frac{dN_i}{dt} = \begin{cases} TP_{i-1} \cdot N_{i-1} - (D_i + TP_i) \cdot N_i, N_i < Max_i \\ 0, N_i \geq Max_i \end{cases}, i = 2, \dots, n-1 \\ \frac{dN_i}{dt} = \begin{cases} TP_{i-1} \cdot N_{i-1} - D_i \cdot N_i, N_i < Max \\ 0, N_i \geq Max \end{cases} \dots\dots\dots i = n \\ Max_i = \frac{P_i}{WC_i}, \dots\dots\dots i = 2, \dots, n \end{array} \right.$$

This is because seeds come only from individuals at the mature and over-mature stages. At the over-mature stage, no transition is made to a next stage, as a result that the over-mature stage is the last one in the *U. pumila* life cycle. Thus, the number of individuals in at the over-mature stage

was described with a different equation (*i.e.*, 3rd equation). In addition, N was the number of individuals at each of the five stages, B was birth rate, D was death rate, TP was the transition probability (*i.e.* the probability associated with a pine population at one age-stage shifting to another age-stage). P was precipitation, which followed normal distribution in this study, and WC was water consumption per individual at each of the study developmental stages, but the seed stage.

Each stage was linked to the following stage through a transfer probability. The mature and over-mature tree stages were linked to the seed stage, as seeds are produced in these two stages. *U. pumila* trees die to a stage-specific rate, except for the seed stage. The seeds became seedlings to a specific germination rate (Tab. 1). The long-term precipitation data were collected from various Wulanaodu regions (42°29' - 43°06' N, 119°39' - 120°02' E, 480m a.s.l.), located at the Horqin Sandy Land in northeastern China (Tang *et al.*, 2014). This region has a semi-arid climate and a typical landscape which includes active sand dunes, stabilized sand dunes, and inter-dune lowlands (Jiang *et al.*, 2014). Besides *U. pumila* trees, there are also typical shrubs, like *Salix gordejewii* and *Artemisia halodendron*, and perennial and annual herbs, such as *Aristida adscensionis*, *Agriophyllum squarrosum* and *Setaria viridis* (Cao *et al.*, 2011).

We obtained 56 years of annual precipitation data (1958-2013) from the China Meteorological Data Sharing Service System to estimate the expectation and variation of the precipitation distribution in the Wulanaodu region (China Meteorological Data Sharing Service System, 2015). Other parameters used as input variables in the model included seed production, death rate, seed germination rate, period of each study morphological stage, transition probability between subsequent developmental morphology stages, and water requirements (Tab. 1).

Model validation and simulation

We used a unit-consistency test to validate this model. The unit-consistency test, which checks for agreement among units, was automatically completed in the Vensim package (Tang *et al.*, 2014). The model was formulated and simulated using a professional SD software package ‘Ventana Simulation Environment Personal Learning Edition (Vensim PLE)’. The simulation was run for 100 times, where each time represented 1 year.

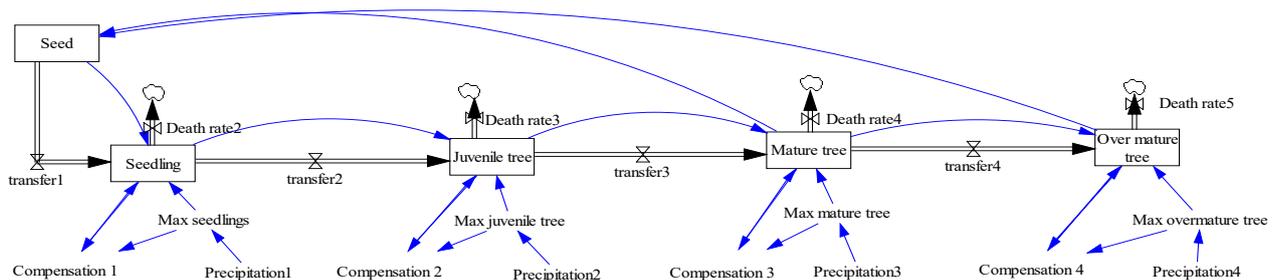


FIGURE 1. Stock-flow diagram representing the simulated system.

TABLE 1

Input parameters for the five developmental morphology stages of *U. pumila* population in the SD model

Full names	Seed	Seedling	Juvenile tree	Mature tree	Over-mature tree	Source
Seed production (seeds/m ²)	-	-	-	2456	7744	Gu et al. 2012
Death rate (%)	-	0.268	0.133	0.346	0.941	Li et al. 2011
Expectation in precipitation (mm)	352	352	352	352	352	http://data.cma.cn
Variance in precipitation	8627	8627	8627	8627	8627	http://data.cma.cn
Seed germination rate (%)	-	-	-	10	10	Tang 2011
Period of stages (years)	1	5	15	30	50	Zhang 2011
Transition probability (%)	-	20	6.67	3.33	2	-
Water consumption (L/individuals/year)	-	21.6	1680.7	1977	1977	Li 2003;Guo et al. 2008;Tian 2009; Ma 2010

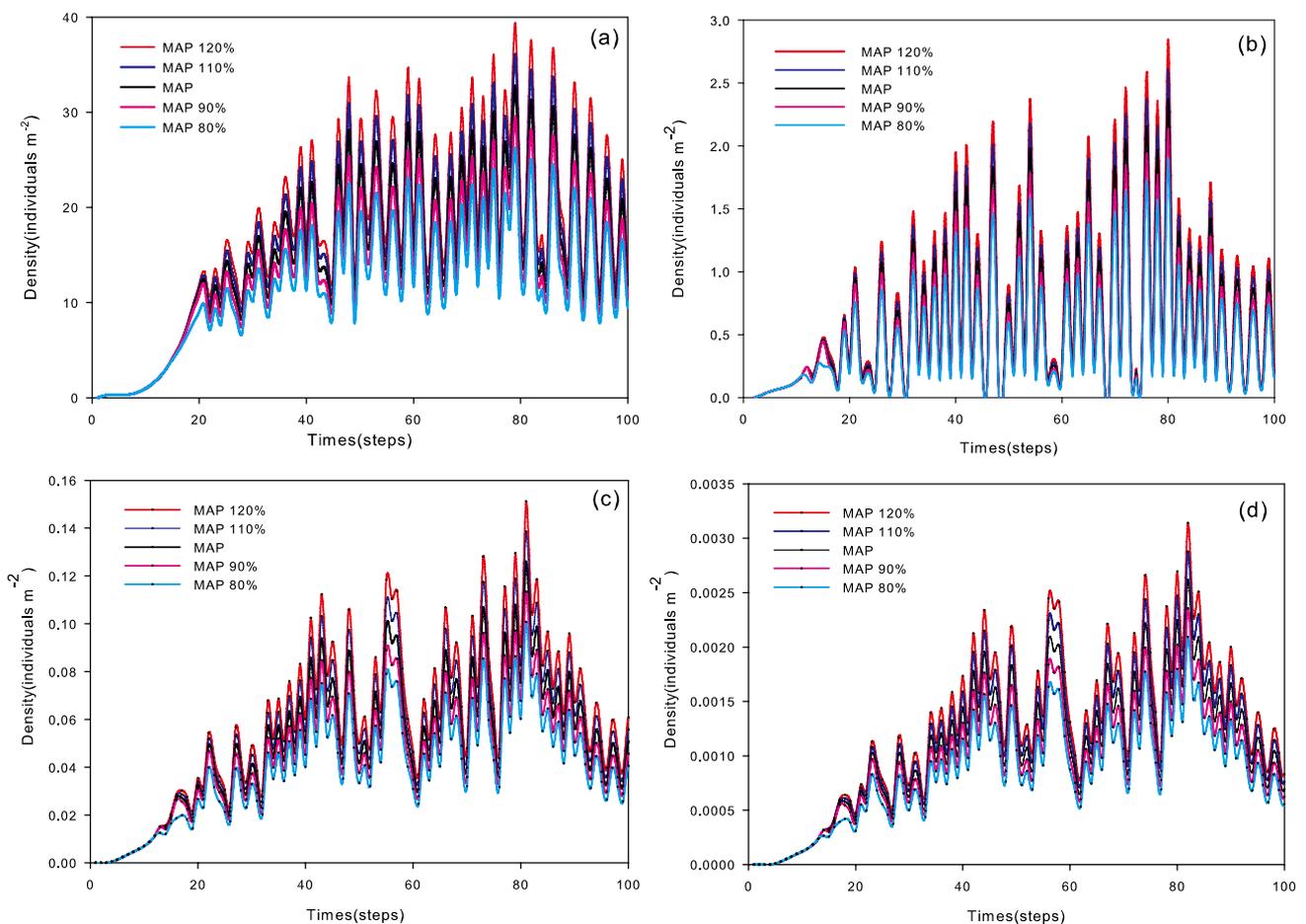


FIGURE 2. Simulation results of *U. pumila* tree densities under different precipitation levels. (A) Seedling stage; (B) Juvenile trees; (C) Mature trees; (D) Over-mature trees. Please note the change of scale among the panels.

Scenario analysis

We evaluated the effects of changes in precipitation on plant population density and age structure. A scenario was designed to represent the mean annual precipitation (MAP). A MAP value of more than 100% was used to represent an increase in precipitation, whereas a value below 100% was

used to represent a decrease in precipitation. Five scenarios were considered in this study (i.e. 120% MAP, 110% MAP, 100% MAP, 90% MAP, and 80% MAP). In each scenario, overall population density, and seedling, and juvenile, mature and over-mature tree densities were tested.

Results

Population densities vs. precipitation levels

The mean population densities, after averaging all stages of developmental morphology within each MAP (from MAP 120% to MAP 80%) were 18.49 individuals/m², 17.01 individuals/m², 15.54, individuals/m², 14.06 individuals/m² and 12.49 individuals/m², respectively. At the end of the simulation period (i.e. after 100 runs of the software), and after averaging all stages of developmental morphology within each MAP, population densities obtained with precipitation levels from 80% to 120% MAP increased from 16.67 to 25.01 individuals/m², respectively. The order of population density under the different MAPs, and after averaging all stages of developmental morphology within each MAP, was 120% of MAP > 110% of MAP > 100% of MAP > 90% of MAP > 80% of MAP (Tab. 2).

TABLE 2

Descriptive statistics of population densities (individuals/m²) under different precipitation levels

	MAP 120%	MAP 110%	MAP	MAP 90%	MAP 80%
Min.	0.20	0.20	0.20	0.20	0.20
1st Qu.	13.14	12.05	11.24	10.13	8.99
Median	18.40	16.87	15.33	13.8	12.27
Mean	18.49	17.01	15.54	14.06	12.49
3rd Qu.	25.05	22.97	20.88	18.79	16.7
Max.	39.77	36.45	33.14	29.83	26.51
End point	25.01	22.93	20.84	18.76	16.67

Other aspects of population structure under the different precipitation levels

The reductions in population densities of *U. pumila* fluctuated among the various stages (Fig. 2). At the end of the simulation period, the maximum and minimum seedling densities were 23.81 (120% MAP) and 15.88 (80% MAP) individuals/m², respectively (Fig. 2). Seedling densities were 21.83, 19.84 and 17.86 individuals/m² in the presence of 110%, 100% and 90% MAP, respectively (Fig. 2a). In the same period, the maximum (1.15 individuals/m²) and minimum (0.76 individuals/m²) densities of juvenile trees occurred in scenarios with 120% MAP and 80% MAP, respectively. The densities of juvenile trees at 110% MAP, 100% MAP and 90% MAP were 1.05, 0.95 and 0.86 individuals/m² separately (Fig. 2b). The maximum and minimum densities on mature trees were 0.05 (100% MAP) and 0.03 (80% MAP) individuals/m² (Fig. 2c). Densities of mature trees under 110% MAP, 100% MAP and 90% MAP were 0.04, 0.04 individuals/m² and 0.03 individuals/m², respectively (Fig. 2c). The maximum and minimum densities in over-mature trees were 0.0012 and 0.0008 individuals/m² at scenarios of 120% MAP and 80% MAP after running the software 100 times (Fig. 2d). At this time, densities in over-mature trees at 110% MAP, 100% MAP and 90% MAP were 0.0011 individuals/m², 0.0011 individuals/m² and 0.0010 individuals/m², respectively (Fig. 2d).

Stability in population structure

At all precipitation levels, seedling made up the largest

proportion of the population structure. They accounted for 95.23% of the total population structure. At the same time, juvenile, mature and over-mature trees constituted 4.58%, 0.19% and 0.01% of the total population structure (Fig. 3).

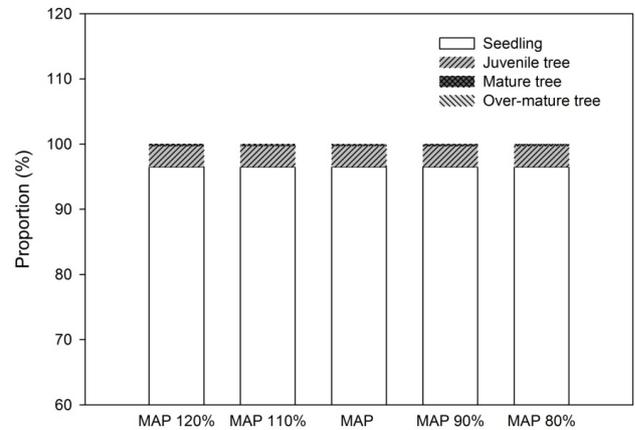


FIGURE 3. Proportion of specific-stages of *U. pumila* population under different precipitation levels.

Discussion

Population density declined as MAP also declined when all stages of developmental morphology were averaged within each MAP; the order was as follows: MAP 120% > MAP 110% > MAP > MAP 90% > MAP 80%. This indicates that *U. pumila* population density increased with increases in precipitation (after averaging all developmental morphology stages within each MAP). These results suggest that precipitation could regulate population density of *U. pumila* trees in sparse woodlands. This is consistent with previous studies, which reported that drought stress reduced growth of *U. pumila* seedlings in northern Mongolia (Dulamsuren *et al.*, 2009b). In arid lands, drought can influence the emergence, survival and mortality of plants (Cipriotti *et al.*, 2008; McAuliffe and Hamerlynck, 2010). In sparse elm woodlands, a lack of water supply might increase the intensity of competition for water among the individuals of an *U. pumila* population, which can lead to the self-thinning of *U. pumila* trees (Zhang *et al.*, 2016). Therefore, our results indicate that *U. pumila* population density would increase with higher precipitation, and decrease with lower precipitation levels (after all stages of developmental morphology were averaged within each MAP).

Climate changes might lead to a drying trend in mid-latitudes, where the Horqin Sandy Land is located (Trenberth *et al.*, 2014). The drying trend in the Horqin Sandy Land is supported by evidence gathered by other investigators (Zhang *et al.*, 2012). They reported an annual decreasing precipitation rate of 13.54 mm/year in the Horqin Sandy Land. The decrease in precipitation decreased very little *U. pumila* population density, but anyhow this might contribute to cause further land degradation. In the scenario of mean annual precipitations, the densities of seedlings, and juvenile, mature and over-mature trees were 19.8, 0.95, 0.04 and 0.0011 individuals/m², respectively. These values indicate the importance of the developmental morphology stage in determining population

density in *U. pumila* populations. They are larger than those found in previous studies (Tang *et al.*, 2014). It might be that factor other than precipitation can also influence the population structure of *U. pumila* trees. These factors might include grazing, vegetation cover, microhabitats, and disturbances like sand burial on *U. pumila* populations as it has been reported in previous studies (Shi *et al.*, 2004; Dulamsuren *et al.*, 2009a; Tang *et al.*, 2014). Also, it has been suggested that the interaction among factors influencing *U. pumila* populations should be considered in future studies.

The proportions of seedlings, and juvenile, mature and over-mature trees were the same under the different water levels (Fig. 3). Also, densities appeared to decrease very little with decreasing precipitation at any of the study stages (Fig. 2). This would be indicating that precipitation had little effects on the *U. pumila* population characteristics in the Horqin Sandy Land at any specific stage of developmental morphology. The effects of precipitation on *U. pumila* population characteristics were not reported previously. However, their effects on population characteristics have been reported previously on other plant species. For instance, it is reported that sexual dimorphism in *Corema album* populations could be changed by precipitation (Alvarez-Cansino *et al.*, 2013). Differences in size between females and males of *Populus cathayana* exposed to different precipitation levels were attributed to different water use efficiencies between both sexes (Xu *et al.*, 2008). However, efficiencies of water use have not yet been reported for *U. pumila* trees. In the Horqin Sandy Land, besides precipitation, *U. pumila* trees can also use soil water present to a depth of up to 4 m (Li *et al.*, 2003). Therefore, more stage-specific studies on various plant traits [e.g., water use efficiency; hydraulic lift (Caldwell *et al.*, 1998)] which can influence the responses of *U. pumila* to precipitation are needed.

Conclusions

Our results suggested that precipitation could affect very little *U. pumila* population densities at any age-specific stages of developmental morphology in sparse woodlands. Anyhow, increases in precipitation beyond maximum values (i.e. 120% MAP) tested in this study, could expand population densities of *U. pumila* at any specific stage of developmental morphology. Furthermore, alternative water supply could be provided in addition to the natural rainfall, to maintain a constant tree population of *U. pumila* in the Horqin Sandy Land.

Acknowledgements

This work was supported by the National Nature Science Foundation of China (41870709), the Scientific Research Program of the Education Department of Liaoning province (LYB201613), and China Postdoctoral Science Foundation funded project (2017M611251). We thank Alan Chang at the Liaoning University for her assistance with English language and grammatical editing of the manuscript. C.A. Busso thanks (1) the sabbatical leave given by Universidad

Nacional del Sur and the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET), (2) the Associateship awarded by the Third World Academy of Sciences (TWAS)-UNESCO, and (3) housing, facilities and financial support from the Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, China.

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