

Lagged Response of Planted Haloxylon ammodendron Forests with Different Stand Ages to Rainfall: Postprint

Authors: Ji Shuxin, Wang Lixiang, Saussurea involucreta, Qiao Rongrong, Chang Xueli, Chang Xueli

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Abstract

Rainfall fluctuations are the primary limiting factor for the growth and development of desert vegetation, directly influencing changes in vegetation composition, structure, and function. Haloxylon ammodendron, as one of the dominant species in arid region vegetation, plays a significant role in windbreak and sand fixation as well as water conservation. The objective of this study is to understand the response process of vegetation productivity in artificial Haloxylon ammodendron plantations of different stand ages to rainfall events. This study focuses on artificial Haloxylon ammodendron of different stand ages in the desert-oasis transition zone of the middle reaches of the Heihe River, based on time series MODIS-NDVI (approximating annual productivity) daily data and corresponding daily rainfall data from May 1 to September 31, 2017-2018, and analyzes the lagged response of NDVI to different rainfall levels using threshold models and statistical methods. The results show: When rainfall is less than 2 mm, the NDVI growth rate of Haloxylon ammodendron across different stand ages exceeds 5%, with those older than 40 years responding most rapidly, exhibiting a growth rate of 10%-56%; at 2-5 mm, the 10-20 year age class shows the largest variation amplitude, with a growth rate of 11%-83%; at 5-10 mm, the 20-40 year age class is the most sensitive, with the growth amplitude reaching up to 170%; when rainfall exceeds 20 mm, the NDVI growth rate of stands older than 40 years is greater than that of the other three age classes, with the maximum increase reaching 76%. After rainfall, the NDVI response time differs among artificial Haloxylon ammodendron plantations of different stand ages, being 7.4 (± 2.8) days for the 0-10 year class, 8.3 (± 3.1) days for the 10-20 year class, 8.1 (± 2.7) days for the 20-40 year class, and 8.2 (± 3.2) days for stands older than 40 years. Rainfall pulses are the key factor driving rapid changes in vegetation productivity in the desert-oasis transition zone.

Haloxylon ammodendron of different stand ages exhibits different response patterns to different rainfall levels; under rainfall conditions of 2–10 mm, artificial Haloxylon ammodendron plantations show the largest NDVI increase, which is higher than the NDVI response variation amplitude under the other two rainfall magnitude categories. Based on the above analysis, it can be inferred that under conditions dominated by rainfall of less than 10 mm in the desert-oasis transition zone, artificial Haloxylon ammodendron plantations aged 10–20 years and 20–40 years play the most important role in the protection system.

Full Text

Preamble

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Introduction

Rainfall pulses represent the most critical constraints on the growth and succession of desert vegetation, directly influencing changes in vegetation composition, structure, and function. As a dominant species in artificial vegetation systems of arid zones, *Haloxylon ammodendron* plays a crucial role in windbreak formation, sand fixation, and water conservation. This study investigates the response of vegetation productivity in artificial *H. ammodendron* woodlands to rainfall events across different stand ages.

The research focuses on *H. ammodendron* woodlands of varying ages in the desert-oasis transition zone of the Heihe River middle reaches. Using MODIS-NDVI time series data (as a proxy for approximate annual productivity) from May 1, 2017, to September 31, 2018, combined with corresponding daily rainfall records, we employed a threshold-delay model and statistical methods to analyze the lag response processes of NDVI to different rainfall levels.

Previous studies have demonstrated the importance of small rainfall events in arid ecosystems. Huang et al. [4] showed that ephemeral plants mediate ecosystem carbon exchange responses to increased precipitation in temperate deserts. Research in the Gurbantünggüt Desert southern fringe [9–10] revealed that rainfall interception loss by sand-fixing shrubs significantly affects water availability. The threshold-delay model has been widely applied to quantify vegetation responses to precipitation pulses, with typical lag times ranging from 8 to 20 days depending on vegetation type and environmental conditions [11].

Study Area and Methods

2.1 Data Collection

MODIS-NDVI data were acquired for the period May 1, 2017, to September 31, 2018, covering the growing season. Daily rainfall data were obtained from meteorological stations within the study area. The research site is located in the desert-oasis ecotone of the Heihe River middle reaches [Figure 1: see original paper].

2.2 Threshold-Delay Model

The threshold-delay model was used to quantify the relationship between rainfall events and NDVI responses. The model parameters include:

- **Rainfall thresholds (R):** Minimum precipitation required to trigger NDVI response
- **Lag time (τ):** Time delay between rainfall event and maximum NDVI response
- **Growth rate (δ):** Magnitude of NDVI change following rainfall

The model structure is defined as:

$$\delta_t = \begin{cases} 0, & R_{t-\tau} \leq R_L \\ \delta_{max} \cdot \frac{R_{t-\tau} - R_L}{R_U - R_L}, & R_L < R_{t-\tau} < R_U \\ \delta_{max}, & R_{t-\tau} > R_U \end{cases}$$

where R_L and R_U represent lower and upper rainfall thresholds, respectively, and δ_{max} denotes the maximum potential growth rate.

Results

3.1 Rainfall Characteristics

During the 2017-2018 study period, rainfall events were predominantly small-scale events. Precipitation less than 2 mm accounted for 51.7% of all rainfall events, with an average event size of 1 mm. Events ranging from 5-10 mm constituted 20.7% of the total, averaging 7.8 mm per event. Rainfall exceeding 10 mm represented only 13.8% of events [Figure 2: see original paper].

The study area exhibited a mean annual precipitation of 111.95 mm during 2017-2018, slightly higher than the 1981-2010 average of 109.7 mm [14]. The growing season (May-September) concentrated 70% of annual rainfall, with precipitation frequency highest during June-August.

3.2 NDVI Response to Rainfall by Stand Age

The NDVI growth rate (δ) varied significantly across stand age groups (0-10 years, 10-20 years, 20-40 years, and >40 years) and rainfall levels.

Table 2. Parameters of the threshold-delay model by stand age

Stand Age (years)	<u>_max</u>	R_L (mm)	Lag Time (days)	R_U (mm)	Growth Rate
0-10	0.384	0.312	7.4 ± 2.8	0.2	0.107
10-20	0.836	0.403	8.3 ± 3.1	0.2	0.236
20-40	1.706	0.351	8.1 ± 2.7	0.2	0.221
>40	0.892	0.349	8.2 ± 3.2	0.2	0.117

For rainfall < 2 mm: All stand ages showed NDVI growth rates exceeding 5%, with stands >40 years responding fastest (growth rates fluctuating 10-56%). This indicates that even minimal precipitation can trigger physiological responses in mature *H. ammodendron* stands.

For rainfall 2-5 mm: The 10-20 year age group exhibited the largest growth rate, ranging from approximately 11% to 83% [Figure 4b: see original paper]. Younger stands (0-10 years) showed moderate responses (12-24%, mean 21%), while the 20-40 year group displayed lower sensitivity.

For rainfall 5-10 mm: The 20-40 year stands demonstrated the highest sensitivity, with maximum growth rates reaching 170% (mean 49%). The 0-10 year group showed growth rates of 2-37% (mean 14%), while 10-20 year stands ranged from 17-66% (mean 36%) [Figure 4c: see original paper].

For rainfall > 20 mm: Stands >40 years showed superior performance compared to other age groups, with NDVI increases up to 76%. The response time for this rainfall level averaged 10.3 (±4.2) days for the >40 year group, 9.3 (±4.5) days for 20-40 years, and 6.3 (±1.3) days for 10-20 years.

3.3 Lag Response Characteristics

The lag time between rainfall events and peak NDVI response varied by stand age: - **0-10 years:** 7.4 (±2.8) days - **10-20 years:** 8.3 (±3.1) days - **20-40 years:** 8.1 (±2.7) days - **>40 years:** 8.2 (±3.2) days

For a specific rainfall event on June 20, 2017 (8.4 mm), the response times were 8 days (0-10a), 10 days (10-20a), 8 days (20-40a), and 6 days (>40a) [Figure 6: see original paper].

3.4 Correlation Analysis

Pearson correlation analysis revealed varying relationships between NDVI growth rate and environmental drivers across stand ages .

Table 4. Correlation between NDVI growth rate and its drivers at different habitats

Driver	0-10 years	10-20 years	20-40 years	>40 years
Rainfall amount	0.546 (P=0.102)	0.313 (P=0.378)	0.345 (P=0.304)	0.338 (P=0.340)
Rainfall frequency	0.347 (P=0.326)	0.175 (P=0.630)	0.023 (P=0.949)	0.187 (P=0.604)
Temperature	0.098 (P=0.768)	-0.087 (P=0.810)	0.334 (P=0.345)	0.020 (P=0.956)

The correlations were generally weak to moderate, with only the 0-10 year group showing a marginally significant relationship with rainfall amount ($r=0.546$).

Discussion

The differential responses of *H. ammodendron* stands to rainfall pulses reflect age-dependent physiological and structural characteristics. Mature stands (>40 years) exhibited rapid responses to small rainfall events (<2 mm), likely due to well-developed root systems enabling efficient water uptake from shallow soil layers [18]. In contrast, intermediate-aged stands (10-40 years) showed maximal growth rates under moderate rainfall (2-10 mm), suggesting optimal resource use efficiency during peak growth phases.

The observed lag times (6-10 days) align with previous research in temperate deserts [19], where NDVI responses typically peak within 8-20 days post-rainfall. The slightly shorter lags for younger stands may reflect faster canopy development and leaf turnover rates.

Small rainfall events play a disproportionately important ecological role in semi-arid regions [20], constituting the majority of precipitation events despite their low individual volumes. Our findings indicate that *H. ammodendron* woodlands, particularly those aged 10-40 years, are highly effective at capturing and utilizing these small pulses, with growth rates increasing up to 170% following 5-10 mm events.

The threshold-delay model effectively captured the nonlinear relationships between rainfall and NDVI responses. The lower threshold (R_L) values around 0.2-0.4 mm indicate minimal rainfall requirements for detectable physiological responses, consistent with the high water-use efficiency of desert shrubs.

Conclusion

Rainfall pulses drive rapid changes in vegetation productivity in desert-oasis transition zones. Artificial *H. ammodendron* woodlands demonstrate age-specific response patterns to different rainfall levels, with maximum NDVI increases occurring when rainfall ranges from 2-10 mm. When the desert-oasis transition zone receives predominantly <10 mm rainfall events, 10-20 year

and 20-40 year old artificial *H. ammodendron* woodlands serve as the most important components of the protection system. These findings have significant implications for ecological restoration and management of arid land vegetation.

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Authors: JI Shu-xin, WANG Li-xiang, BAI Xue-lian, QIAO Rong-rong, CHANG Xue-li

Affiliation: Department of Resources and Environmental Engineering, Ludong University, Yantai 264025, Shandong, China

Abstract: Rainfall pulses are the most important constraints for the growth and succession of desert vegetation and directly affect the changes in vegetation composition, structure, and function. As one of the dominant species of artificial vegetation in the arid zones, *Haloxylon ammodendron* is a crucial factor in windbreaking, sand fixation, and water conservation. The objective of this study is to understand the response of the vegetation productivity of the artificial *H. ammodendron* woodlands to rainfall events at different stand ages. We studied the *H. ammodendron* woodlands exhibiting different stand ages in a desert-oasis transition zone in the middle reaches of the Heihe River using the MODIS-NDVI (the approximate annual productivity) time series from May 1, 2017, to September 31, 2017. Based on the corresponding daily rainfall data, a threshold model and statistical methods were used to analyze the lag response process of the NDVI to different rainfall levels. The results showed that (1) When the rainfall was less than 2 mm, the NDVI growth rates in case of different stand ages were more than 5% and stands with ages of more than 40 year reacted the fastest; the growth rates fluctuated from 10% to 56%. When the rainfall was 2-5 mm, the stands that exhibited ages of 10-20 years showed the largest growth rate, i.e., from approximately 11% to 83%. When the rainfall was 5-10 mm, the most sensitive group had stand ages of 20-40 year, with the highest growth rate being 170%. When the rainfall was more than 20 mm, the NDVI growth rate was greater for stand ages greater than 40 year than those for the remaining three stand ages, with an increase of up to 76%. (2) After the rainfall, the NDVI response time was observed to be different for different stand ages: 7.4 (± 2.8) days for the 0-10 year group, 8.3 (± 3.1) days for the 10-20 year group, 8.1 (± 2.7) days for the 20-40 year group, and 8.2 (± 3.2) days for the >40 year group. (3) Rainfall pulses contribute to rapid changes in vegetation productivity in the desert-oasis transition zone. Different stand age groups showed different response patterns to different rainfall levels, and the NDVI increase for the artificial *H. ammodendron* woodland was the largest when the rainfall was 2-10 mm. According to these results, when the desert-oasis transition zone is dominated by less than 10 mm of rainfall, the roles of 10-20 year and 20-40 year artificial *H. ammodendron* woodlands in the protection system are likely to be the most important factors.

Keywords: stand age; artificial *Haloxylon ammodendron* woodland; rainfall; NDVI; Threshold-delay model; lag response; Linze oasis

Note: Figure translations are in progress. See original paper for figures.

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