Postprint: Coupling Relationship Between Non-irrigated Haloxylon ammodendron Plantation Growth and Soil Moisture Dynamics

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Abstract

To investigate the ecological characteristics of non-irrigated artificial Haloxylon ammodendron forests under takyr soil site conditions in the desert-oasis ecotone of the Gurbantünggüt Desert and to determine the optimal planting density for stands, we conducted a 38-year (1983–2021) investigation of initially planted H. ammodendron, natural regeneration seedlings, and soil moisture at different slope positions in water-harvesting afforestation sites in Mosuowan. We examined the response of H. ammodendron growth to density variations, analyzed the changing characteristics of soil moisture across different forest sites, and explored the relationship between H. ammodendron growth and soil moisture, aiming to provide a scientific basis for the establishment and sustainability of artificial H. ammodendron forests. The results indicated: (1) Mother tree survival rate was highest at an afforestation density of 6 m × 3.5 m (480 plants$\cdot$hm^{-2}). As afforestation density increased, both mother tree preservation rate and the natural regeneration ratio of H. ammodendron gradually decreased. Forest sites with higher mother tree retention density exhibited poorer growth performance and lower biomass. Sites with higher coverage and canopy density impeded shallow soil moisture recharge, leading to poorer growth performance and biomass of H. ammodendron regeneration seedlings. (2) Tree growth of H. ammodendron mother trees showed a significant negative correlation with soil water content at 140–280 cm depth in the root zone ($P<0.05$), and primarily utilized soil moisture at 140–240 cm depth. Comparison of the three forest sites revealed that sites with higher soil moisture content in this layer exhibited better mother tree growth performance and higher biomass. (3) At a mother tree retention density of 360 plants$\cdot$hm^{-2} (spacing 4 m × 7 m), H. ammodendron demonstrated better growth performance, highest overall biomass, richer understory vegetation, and relatively better soil moisture conditions. In summary, maintaining this density during water-harvesting afforestation in this region is more conducive to structural stability of non-irrigated artificial H. ammodendron forests and sustained windbreak and sand fixation benefits.

Full Text

Preamble

Coupling Relationship Between Growth and Soil Moisture Change of Haloxylon ammodendron Plantation Without Irrigation

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Abstract: To investigate the ecological characteristics of no-irrigation artificial Haloxylon ammodendron forests under takyr soil conditions in the desert-oasis transition zone of the Gurbantunggut Desert and to determine the optimal planting density for stand establishment, this study examined the initial plantings, natural regeneration seedlings, and soil moisture at different slope positions in water-harvesting afforestation sites at the Mosuowan Desert Research Station over a 38-year period (1983-2021). The growth response of H. ammodendron to density variations was analyzed, and the variation characteristics of soil moisture in each forest plot were studied. The relationship between H. ammodendron growth and soil moisture was explored to provide a scientific basis for the construction and sustainability of artificial H. ammodendron forests. The results showed that: (1) When the afforestation density was 6 m × 3.5 m (480 plants hm^{-2}), the mother tree survival rate was highest. As afforestation density increased, both the mother tree preservation rate and the natural regeneration ratio gradually decreased. Stands with higher mother tree retention density exhibited poorer growth and lower biomass. Higher canopy density and coverage hindered shallow soil moisture recharge, resulting in poorer growth and biomass of H. ammodendron regeneration seedlings. (2) There was a significant negative correlation between mother tree growth and soil moisture at root depths of 140-280 cm ($P < 0.05$). Soil moisture in the 140-240 cm layer was the primary water source. Comparison of the three stands revealed that higher soil moisture content in this layer corresponded to better mother tree growth and higher biomass. (3) When the mother tree retention density was 360 plants hm^{-2} (spacing 4 m × 7 m), H. ammodendron showed better growth, highest overall biomass, richer understory vegetation, and relatively better soil moisture conditions. In summary, maintaining this density for water-harvesting afforestation in this region is more conducive to maintaining stable structure and continuous windbreak and sand fixation benefits in no-irrigation artificial H. ammodendron forests.

Keywords: takyr soil; artificial Haloxylon ammodendron forest; catchment afforestation; growth characteristics; soil moisture

Haloxylon ammodendron is a perennial shrub-like small tree in the Chenopodiaceae family, mainly distributed in the deserts of northwestern China. It exhibits characteristics of drought resistance, wind erosion tolerance, high temperature resistance, cold resistance, and barren tolerance. Since the 1950s, H. ammodendron has been the preferred species for artificial afforestation around the Gurbantunggut Desert. The Junggar Basin is located in an arid region with scarce water resources, severe wind-sand hazards, and a fragile ecological environment. As the largest and most concentrated species in this desert, H. ammodendron forms a natural barrier protecting the oasis edges of the Junggar Basin from dust storm erosion. However, over the past half-century, climate change and human factors such as over-harvesting, grazing, and unreasonable reclamation have reduced H. ammodendron population area in the Junggar Basin, severely fragmenting the landscape. The normal seedling recruitment mechanism of H. ammodendron populations has been seriously threatened, with population age structure generally showing decline and communities exhibiting retrogressive succession characteristics. Meanwhile, the drifting sand area in the Gurbantunggut Desert continues to increase, and desertification is becoming increasingly severe. The preservation rate of planted H. ammodendron is very low, and it is particularly difficult to obtain seedlings on takyr soil.

In 1985, Huang Pizhen et al. conducted no-irrigation afforestation on takyr soil in the Mosuowan area using water-harvesting measures. In the early stage of afforestation, the average survival rate of H. ammodendron reached 91.1%. Vegetation recovered well, wind-sand disasters were significantly reduced, and good ecological and social benefits were achieved. However, under the background of warming and wetting trends in the climate of Central Asian arid regions, the climate and hydrological situation in the project area have changed in recent years. It is unclear what impact these changes will have on no-irrigation artificial H. ammodendron forests, what the current growth status of the stands is, and what causes the observed differences. For H. ammodendron forests established with water-harvesting afforestation measures, this study selected stands with different planting densities as research objects, set up sample plots, and conducted vegetation community surveys, monitoring, sampling, analysis, and evaluation to clarify the stand growth and structural characteristics of different density H.

ammodendron forests under no-irrigation water-harvesting afforestation conditions, explore the mutual influence between H. ammodendron growth and soil moisture, and provide theoretical basis and technical support for artificial H. ammodendron forest construction at oasis edges.

1. Materials and Methods

1.1 Study Area Overview

The study area is located at the Mosuowan Desert Research Station (45°02 N, 86°06 E, elevation 346 m) on the southwestern edge of the Gurbantunggut Desert, in the transition zone between desert and oasis. This region has a temperate continental arid climate with an average annual temperature of 6.6 °C, annual precipitation of less than 120 mm, and evaporation as high as 1942 mm. The groundwater level is approximately 27 m, and snow cover thickness is about 13 cm, reaching up to 30 cm at maximum. In spring (March–April), rising temperatures cause frozen soil and snow to melt while evaporation remains weak, increasing soil moisture. The zonal soil is desert sierozem, with some areas experiencing alkalinization. Artificial H. ammodendron forests were planted in 1983, and no artificial irrigation has been applied since afforestation.

1.2 Selection of Study Materials

We selected H. ammodendron forest plots that employed water-harvesting measures, specifically those established on flat takyr soil using the method of digging collection ditches. Ditches were opened in autumn 1983, with soil turned up on both sides to a depth of 25 cm. H. ammodendron seedlings were planted in the ditch bottom in 1984 at 1–6 m spacing, with planting holes dug at 3–10 m spacing. Based on differences in ditch distance and plant spacing in each water-harvesting afforestation plot, this study selected different afforestation densities of H. ammodendron shelterbelt systems as research objects.

1.3 Observation Plot Setup

In July 2021, using typical sampling methods, we selected H. ammodendron standard plots (basically undisturbed by humans or pests) with initial afforestation densities of 1.5 m × 7 m, 4 m × 4 m, and 6 m × 3.5 m, all with north-south oriented water-harvesting ditches. Each plot measured 20 m × 50 m. In each plot, we established 1 m × 1 m understory vegetation survey quadrats along the diagonal direction (Figure 2). We also set up observation points at the ridge top, slope middle (midpoint between ridge top and H. ammodendron root), and root position (10 cm from the root of H. ammodendron in the inter-ridge area) for soil moisture monitoring.

1.4 Haloxylon ammodendron Growth Observation

In July 2021, we measured all H. ammodendron individuals in each 20 m × 50 m plot, investigating plant height, crown width, ground diameter, dead branch ratio, health status, and understory vegetation coverage. Based on precise root location and field measurements of plant height, crown width, and ground diameter, we classified H. ammodendron in each plot into mother trees (initial artificial plantings), saplings, and seedlings (plant height $\leq$ 40 cm). In each plot, we used the zigzag method to select representative standard sample plants (3 mother trees and 3 natural regeneration seedlings), marked them with flags, and measured plant height, crown width, ground diameter, and new branch growth monthly from May to September.

1.5 Tree Biomass Calculation

This study used the regression model established by Li Gangtie et al. to calculate individual H. ammodendron biomass. The model' s multiple correlation coefficient was 86.5%. Individual plant biomass was accumulated to obtain the biomass of the entire study forest.

$$BW = 0.01 + 0.204 + 1.417 + 5.067 + 0.243$$

$$RW = -1.509 + 6.031 + 1.722 + 8.603 + 0.399$$

Where BW is aboveground biomass (kg plant^{-1}), RW is belowground biomass (kg plant^{-1}), H is plant height (cm), E is crown width (cm), and R is ground diameter (cm).

1.6 Soil Moisture Measurement

In each plot, we selected 3 representative and well-growing mother trees in areas with good H. ammodendron preservation. We installed 3 soil moisture detection tubes at the inter-plant position, root position, and slope middle position of each tree (Figure 2). Soil moisture was measured monthly from May to September using a TRIME soil moisture tester, reading volumetric water content every 20 cm in the 0–280 cm soil layer.

1.7 Data Processing and Analysis

We used SPSS 20.0 software for data organization and analysis. One-way ANOVA was used for significance testing at a 95% confidence level, with all statistical analyses performed at extremely significant levels. Spearman correlation analysis was used to examine the interactive effects between H. ammodendron plant height (H), crown width (E), ground diameter (R), aboveground biomass (BW), belowground biomass (RW), total biomass (BW+RW) and soil moisture at ridge top, slope middle, root position, inter-plant position, and different root depths. Origin 2021 software was used for graphical presentation.

2. Results

2.1 Haloxylon ammodendron Preservation and Growth Characteristics

2.1.1 Haloxylon ammodendron Preservation and Natural Regeneration As shown in Table 1, the mother tree preservation rate (excluding withered, prostrate, and broken trees) in each density plot increased with decreasing afforestation density, with the low density being significantly higher than medium and high densities. Mother tree retention density was highest in the medium density plot and lowest in the high density plot. The ratio of natural regeneration seedlings to mother trees reflects the population' s natural regeneration capacity. The proportion of H. ammodendron regeneration seedlings was above 1.0 in all plots, with seedlings accounting for about 50%. The natural regeneration ratio in all plots exceeded 1.0, indicating that H. ammodendron forests of various densities maintain good regeneration capacity and sustainability under long-term no-irrigation conditions, with lower density stands showing better natural regeneration capacity.

Canopy density and understory vegetation coverage directly affect the protective effectiveness of sand-fixing forests. Canopy density in all plots exceeded 0.4, and the trend of canopy density and understory vegetation coverage was low density > medium density > high density.

Table 1 Basic characteristics of Haloxylon ammodendron forest plots

Initial afforestation density (m)	Mother tree preservation rate (%)	Natural regeneration ratio	Canopy density	Understory vegetation coverage (%)
1.5 × 7	83.33	1.08ab	0.49b	1.04b
4 × 4	91.67	1.35a	1.53b	3.63a
6 × 3.5	95.83	2.01ab	2.28a	3.09ab

Note: Different lowercase letters indicate significant differences in growth indices among different density plots ($P < 0.05$).

2.1.2 Haloxylon ammodendron Growth Characteristics Overall Growth and Biomass

As shown in Table 2, the average plant height, crown width, and ground diameter of mother trees in the high density plot were higher than other plots, with biomass trends matching understory vegetation coverage and canopy density (low density > high density > medium density). Total mother tree biomass showed a decreasing trend with increasing mother tree retention density: high density (5.91 $t \cdot hm^{-2}$) > low density (4.91 $t \cdot hm^{-2}$) > medium density (6.20 $t \cdot hm^{-2}$). The average plant height of medium density mother trees was only 158 cm, far lower than high and low densities. The average plant height and ground diameter of medium density natural regeneration seedlings were significantly higher than other plots, with biomass trends matching natural regeneration seedling biomass (low density > high density > medium density).

The average dead branch ratio of mother trees showed no significant differences among plots, but the average dead branch ratio of low density natural regeneration seedlings was significantly better than medium density plots (Figure 3). Total biomass of H. ammodendron in all plots ranged from 10.23 to 12.11 $t \cdot hm^{-2}$, with the highest value in medium density (12.11 $t \cdot hm^{-2}$) being 2.10 $t \cdot hm^{-2}$ higher than the lowest value in low density (10.01 $t \cdot hm^{-2}$).

Table 2 Biomass of Haloxylon ammodendron forest ($t \cdot hm^{-2}$)

Initial afforestation density (m)	Mother tree biomass	Natural regeneration seedling biomass	Total biomass
	Aboveground	Belowground	Total
1.5 × 7	3.11a	2.98b	6.20ab
4 × 4	2.28a	2.01ab	4.91b
6 × 3.5	5.91a	4.91b	9.02a

Note: Different lowercase letters in the same column indicate significant differences in biomass ($P < 0.05$).

Seasonal Growth Characteristics

Within each afforestation density plot, the growth rate of H. ammodendron during the growing season showed no obvious differences (Figure 4). Mother tree plant height changed little over time (affected by dry tips), while average crown width increased from May to July and then gradually slowed from July to September. Ground diameter showed a gradual increasing trend (except in high density). The plant height, crown width, and ground diameter of regeneration seedlings showed a slow increasing trend from May to September, with the most obvious growth in plant height and ground diameter observed in low density seedlings.

New branch length varied significantly among individuals within each plot. For example, in high density, the longest branch reached 16.94 cm while the shortest was only 1.98 cm. After averaging 3 mother tree standard plants and 3 natural regeneration seedling standard plants, monthly differences were small, with rapid growth from May to July reaching maximum values. At this time, average branch length from largest to smallest was low density (9.21 cm), medium density (8.51 cm), and high density (8.31 cm), decreasing in August due to powdery mildew.

2.2 Soil Moisture Variation Characteristics

2.2.1 Vertical Variation of Soil Moisture As shown in Figure 5, the monthly variation coefficient of surface soil volumetric water content was the largest, mainly affected by precipitation and ephemeral plants. In high and low density plots, soil volumetric water content below 20 cm first stabilized and then increased with depth, rising significantly at 220 cm and 260 cm. In the medium density plot, soil water content showed fluctuating changes, with an obvious inflection point at 180 cm. The difference in volumetric water content above and below the 140 cm soil layer was significant. Multiple comparisons revealed extremely significant differences ($P < 0.01$) in volumetric water content above 140 cm between medium density and other plots, and extremely significant differences ($P < 0.01$) in volumetric water content below 140 cm between high density and other plots.

Averaging the values, soil volumetric water content in the 0–140 cm layer was highest in medium density (10.55%), followed by high density (7.46%) and low density (6.45%). In the 140–280 cm layer, soil volumetric water content was highest in high density (6.94%), followed by medium density (4.43%) and low density (4.21%). Overall, within the near-surface 300 cm depth range, soil volumetric water content from largest to smallest was medium density (7.20%), high density (7.49%), and low density (5.33%), with vertical variability showing medium density (7.49%) > high density (5.33%) > low density.

2.2.2 Soil Moisture Variation at Different Observation Points Field surveys showed that the slope of the medium density plot' s collection ditch was close to 0°, with almost no surface runoff. The low density plot had narrower ditch spacing, with precipitation infiltrating along pit walls toward the root area. Soil water content showed the pattern: ridge top > root area > inter-plant > root area. However, the high density plot showed the opposite pattern: root area > inter-plant > ridge top, because the ridge spacing (row spacing) in high density plots was much larger than other plots, allowing large amounts of water to converge in the inter-ridge area and infiltrate into deep root layers.

The trend of soil moisture increasing or decreasing from ridge top to inter-ridge (H. ammodendron root) reflects that different ridge spacing (row spacing) forming sand ridge landforms and slope positions, as well as H. ammodendron root systems, have significant impacts on hydrological processes including precipitation, runoff, infiltration, evaporation, and transpiration.

Table 3 Distribution characteristics of soil moisture at different observation points

Initial afforestation density (m)	Ridge top	Slope middle	Root area	Inter-plant
1.5 × 7	7.46%	6.94%	4.43%	4.21%
4 × 4	10.55%	7.20%	6.45%	5.33%

Initial afforestation density (m)	Ridge top	Slope middle	Root area	Inter-plant
6 × 3.5	6.45%	5.33%	7.46%	6.94%

*Note: Different lowercase letters indicate significant differences ($P < 0.05$), ** indicates extremely significant differences ($P < 0.01$).*

2.3 Correlation Analysis Between Haloxylon ammodendron Growth and Soil Moisture

2.3.1 Correlation Between Mother Tree Growth and Root Soil Moisture As shown in Figure 7, mother tree growth showed no significant correlation with soil moisture above 140 cm depth, but significant negative correlation with soil moisture below 140 cm. In the 140-180 cm layer, all growth indices except belowground biomass showed significant or extremely significant negative correlation with soil moisture. In the 220-280 cm layer, crown width, ground diameter, and aboveground biomass all showed significant or extremely significant negative correlation with soil moisture.

The main water source for forest plots comes from spring snowmelt recharge (March-April). Without micro-topography modification, water from other seasons cannot converge large amounts into deep soil layers. On one hand, affected by soil texture, the study area has takyr soil on the surface, with clay and sandy loam with poor water binding capacity underground. Dry sand forms an isolation layer, while clay below the sand layer retains moisture due to isolation from the upper sand layer, becoming a water reservoir under the sand. In the takyr soil of the Junggar Basin, the heavy clay surface is barren, but the water content of takyr soil is closely related to sand layer thickness. In Central Asia, the 25-30 cm thick surface soil may dry out due to evaporation, but moisture below this layer is preserved for plant use. On the other hand, soil moisture differences are related to H. ammodendron root system absorption and utilization. Comparing root moisture with inter-plant moisture shows that plots with taller mother trees, larger crown widths, and higher understory vegetation coverage have significant interception of precipitation, which is lost through evapotranspiration before reaching the ground, hindering moisture recharge near roots. Mother tree growth and development consume soil moisture below 140 cm at the root area, with particularly obvious absorption of 140-240 cm soil moisture. Meanwhile, due to the inverted "pyramid" root distribution of H. ammodendron, lateral roots widely distributed around the main root mainly consume 60-100 cm deep moisture within 300 cm horizontal distance from the main root, indicating that H. ammodendron compensates for root soil moisture deficits by continuously extending roots to deeper and surrounding soil layers to maintain water balance.

2.3.2 Correlation Between Mother Tree Growth and Inter-Plant Soil Moisture As shown in Figure 8, all growth indices of H. ammodendron were positively correlated with 0–20 cm soil moisture, negatively correlated with 20–40 cm soil moisture (especially ground diameter showing significant negative correlation), and positively correlated with 60–100 cm soil moisture (except belowground biomass), though not significantly.

The area near H. ammodendron roots is fixed sand surface located in inter-ridge areas. Under long-term no-irrigation conditions, the mass water content of soil slopes in H. ammodendron forests of various densities (converted based on measured average soil bulk density of 1.3 $g \cdot cm^{-3}$) is above 4%, which can meet the long-term growth and natural regeneration needs of H. ammodendron. Soil crust and micro-topography differences are also important factors affecting H. ammodendron growth. Higher understory vegetation coverage and surface biological crust coverage significantly intercept precipitation, while H. ammodendron consumes moisture near roots for growth and development. Therefore, medium and low density plots mainly show decreasing soil moisture closer to H. ammodendron roots, while high density plots show the opposite pattern due to much larger ridge spacing that allows large amounts of water to converge for root use.

3. Discussion

The differences in soil moisture among various plots are influenced by surface micro-topography, which causes redistribution and significantly reduces moisture loss through evaporation in deeper soil layers. However, as years increase, the soil micro-topography of some plots tends to become flat, with precipitation evenly distributed on the surface and wetted soil layers often shallow. The main water source in the study area is spring snowmelt. Without micro-topography modification, water from other seasons cannot converge large amounts into deep soil layers. Soil texture also plays a role, with takyr soil being heavy clay that is barren on the surface but whose water content is closely related to sand layer thickness. In Central Asia, surface soil may dry out, but moisture is preserved below for plant use. Additionally, soil moisture differences relate to root system absorption. Comparison of root and inter-plant moisture shows that plots with larger mother trees and higher understory vegetation coverage intercept precipitation that is lost through evapotranspiration, hindering root moisture recharge. Mother trees consume soil moisture below 140 cm, particularly 140–240 cm, while lateral roots mainly use 60–100 cm moisture within 300 cm of the main root, indicating H. ammodendron compensates for root moisture deficits through root extension.

Artificial forests with high planting density will gradually die if soil moisture consumption is not alleviated through thinning. Individuals compete intensely for water, causing strong self-thinning. During water-harvesting ditch construction, some sections may collect excessive water beyond H. ammodendron needs, causing death. Numerous studies show soil moisture is the most critical and direct ecological factor affecting vegetation growth in arid regions. Appropriate H. ammodendron water-harvesting afforestation density should be determined, with measures such as reshaping collection ditches, maintaining reasonable spacing, and thinning implemented according to stand growth changes to redistribute soil moisture and maintain long-term stable stand structure for maximum windbreak and sand fixation benefits.

This study shows that higher H. ammodendron canopy density and understory vegetation coverage lead to poorer 0–140 cm soil moisture and poorer growth and biomass of regeneration seedlings (which mainly use surface soil moisture). Better 0–140 cm soil moisture corresponds to better growth and higher biomass of natural regeneration seedlings. H. ammodendron mainly absorbs root area 140–240 cm soil moisture, and higher moisture in this layer at root areas corresponds to better mother tree growth and higher biomass, similar to previous research results. These findings demonstrate H. ammodendron has strong water absorption and retention capacity.

4. Conclusion

As a pioneer species for sand-fixing afforestation in arid regions, this study examined no-irrigation artificial H. ammodendron forests and their understory soil moisture under takyr soil conditions at desert-oasis edges, yielding the following conclusions:

1) Under different densities, H. ammodendron preservation rates and growth status differed significantly. Preservation rates decreased with increasing afforestation density, with lower retention density stands showing better individual tree growth. Higher coverage and canopy density resulted in poorer 0–140 cm soil moisture and poorer growth and biomass of H. ammodendron regeneration seedlings.

2) H. ammodendron mother tree growth was significantly negatively correlated with root soil moisture at 140–280 cm depth ($P < 0.05$). H. ammodendron mainly utilized root area 140–240 cm soil moisture. Comparison of the three stands showed that higher moisture in this layer corresponded to better mother tree growth and higher biomass.

3) When afforestation density was 6 m × 3.5 m (480 plants hm^{-2}), the post-growth mother tree retention density was only 360 plants hm^{-2}, but total biomass was higher, growth better, understory vegetation richer, and soil moisture conditions relatively better. When afforestation density was 4 m × 4 m (625 plants hm^{-2}), the existing H. ammodendron density was highest but overall growth poorest. When afforestation density was 1.5 m × 7 m (952 plants hm^{-2}), the initial planting preservation rate (83.33%), natural regeneration ratio, canopy density, and understory vegetation coverage were higher than other densities, but regeneration seedling growth, biomass, and sapling numbers were lower. Therefore, when constructing artificial forests on takyr soil in Mosuowan using water-harvesting mea-

sures, maintaining a density of 4 m × 7 m (360 plants hm^{-2}) is an ideal choice.

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