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# Critical deep soil moisture threshold determines *Haloxylon ammodendron* plantation sustainability across desert sites in northwest China

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## Abstract

*Haloxylon ammodendron* plantations are critical for combating desertification in northwestern China's arid regions, yet their sustainability is threatened by deep soil desiccation. While previous studies have documented growth patterns in dryland plantations, critical moisture thresholds and optimal rotation ages across contrasting site types remain poorly quantified. We conducted a chronosequence study across six *H. ammodendron* plantation sites (ages 3–35 years), representing three habitat types—converted cropland, mobile sand dunes, and gravel desert—in Minqin Oasis, northwestern China. We measured growth parameters, soil moisture profiles (0–100 cm depth), and dieback rates. Growth peaked at approximately 25 years (height 386 cm, crown area 11.95 $m^2$), followed by rapid deterioration in 35-year stands with 26% height decline and 68% crown area reduction. Deep soil moisture (60–100 cm) emerged as the dominant limiting factor, exhibiting strong correlations with all growth parameters ($r = 0.68–0.82$, $p < 0.01$). A critical threshold of 2.0% was identified: plantations below this threshold exhibited severe dieback (15–52%) versus 8% above. Converted croplands maintained substantially higher deep moisture (3.04%) than sand dunes (1.64%) and gravel deserts (1.53%), resulting in 45% greater growth rates. Our results provide quantitative criteria for rotation planning: 25–30 years for converted croplands versus 20–25 years for sand dunes, with gravel deserts requiring supplemental irrigation below threshold.

***Keywords:*** *Haloxylon ammodendron*; Deep soil moisture; Critical threshold; Site type; Growth performance

## 1. Introduction

Desertification is one of the most severe global environmental challenges. Between 1982 and 2015, 6% of the world's drylands experienced desertification due to unsustainable land use practices exacerbated by anthropogenic climate change.[1] In China, desertified land covers 2.62 million $km^2$, accounting for 27.3% of the total land area, predominantly distributed across the arid and semi-arid regions of northwest China.[2] To combat desertification expansion, China launched the Three-North Shelter Forest Program in

1978, the world's largest and longest-running ecological restoration project, with cumulative afforestation exceeding 30 million hectares.[3]

Afforestation has played a vital role in windbreak and sand stabilization, local climate amelioration, and ecological function restoration.[4] However, the sustainability of plantations in northwest China's arid regions faces increasingly severe challenges. Historically, oasis–desert ecotones, such as Minqin, featured shallow groundwater tables (3–5 m depth), enabling deep-rooted species, including *Haloxylon ammodendron*, to access the water table and establish a dual water supply system combining precipitation and groundwater.[5,6] Over the past 30–40 years, however, excessive agricultural groundwater extraction coupled with climate change has driven water table decline at rates of 0.5–1.0 m/y, with current depths commonly exceeding 10–15 m and reaching over 30 m in some areas.[7,8] As groundwater depths now exceed the root zone of *H. ammodendron* (typically 8–12 m), plantations have transitioned from "groundwater-supplemented" to "precipitation-dependent" systems.[9] Given the region's extremely low annual precipitation (typically <200 mm) and intense evaporation (>2,000 mm/y), sparse rainfall alone cannot sustain long-term plantation water demands.[10] Chronic water deficits trigger premature stand deterioration and extensive mortality, with many plantations exhibiting growth stagnation and severe dieback within 10–20 years of establishment.[11,12] Consequently, achieving long-term sustainability of *H. ammodendron* plantations under groundwater-inaccessible conditions has emerged as a critical scientific challenge for ecological restoration in oasis fringe zones.

*Haloxylon ammodendron* (Chenopodiaceae) is a dominant and keystone species in temperate desert ecosystems, exhibiting exceptional drought tolerance, salinity tolerance, and sand burial adaptation, with root systems extending beyond 10 m depth. Its rapid growth and effective sand stabilization ability have made it the preferred species for afforestation in northwest China's arid regions, with over 1 million hectares established under the Three-North Shelter Forest Program.[13-15] However, while substantial research has advanced understanding of degradation mechanisms, spatial distribution patterns, and physiological–ecological adaptations, systematic knowledge of whole-lifespan growth dynamics, mature-phase performance, and senescence patterns under declining groundwater conditions remains lacking.[13,16,17]

Soil moisture constitutes the primary limiting factor for plant growth and distribution in arid regions.[18,19] Deep soil moisture (60–100 cm) serves as a critical buffer against drought stress. Compared to shallow soil moisture (0–40 cm), which exhibits high volatility due to evaporation, deep water reserves remain relatively stable.[20,21] However, when planting density is excessive or stand age is prolonged, tree transpiration persistently exceeds precipitation inputs, progressively depleting soil moisture from shallow to deep layers.[22] Deep-rooted species such as *H. ammodendron* preferentially extract water from deeper soil horizons under drought stress, but once deep moisture falls below a critical threshold, plants experience severe water stress manifested as growth cessation, crown dieback, and branch mortality.[23-25] Despite its fundamental importance for sustainable plantation management, this critical moisture threshold—the minimum water content required to maintain normal stand growth—remains unquantified.

Excessive groundwater extraction has resulted in widespread high mortality rates and natural self-thinning in *H. ammodendron* plantations, necessitating continuous replanting to maintain canopy cover and protective functions.[26,27] This passive "establishment–decline–replanting" management paradigm reflects insufficient understanding of stand growth dynamics and site water carrying capacity. Specifically, the following critical scientific questions remain unanswered: (i) How long can *H. ammodendron* plantations sustain healthy growth after losing groundwater support and becoming solely precipitation-dependent? When do stands reach peak growth? (ii) What is the critical threshold for deep soil moisture? How does soil moisture vary across different stand ages, and when does critical depletion occur? (iii) How do different site types (mobile dunes, converted cropland, and gravel desert) differ in water supply capacity? (iv) How do decline trajectories vary with planting density? When is density regulation or replanting most effective? Current research has failed to establish quantitative relationships among stand age, growth performance, and soil moisture status, leaving afforestation practices without scientific criteria for site suitability assessment, stand longevity prediction, replanting timing determination, and planting density optimization.

To address these knowledge gaps, we selected the Minqin oasis–desert ecotone as a representative study area (groundwater depth >20 m, beyond *H. ammodendron* root reach) and employed a chronosequence approach. We systematically sampled *H. ammodendron* plantation sites spanning different stand ages (3–35 years) and site types under similar climatic conditions, measuring stand growth parameters (height, basal diameter, and crown dimensions), vertical soil moisture distribution (0–100 cm), and mortality rates. The study objectives are to: (i) elucidate whole-lifespan growth dynamics of rain-fed *H. ammodendron* plantations, determining peak growth age and decline patterns; (ii) quantify relationships between deep soil moisture and stand growth, identifying the critical moisture threshold for maintaining normal growth; (iii) evaluate water supply capacity of different site types and their influence on plantation sustainability; and (iv) propose management recommendations for density regulation and replanting timing based on growth dynamics, moisture thresholds, and site conditions. The findings will not only advance scientific understanding of plantation growth patterns and water limitation mechanisms under groundwater-inaccessible conditions in arid regions, but also provide theoretical foundations and practical guidance for sustainability optimization of large-scale afforestation programs in oasis–desert ecotones and globally analogous arid regions experiencing similar hydrological transitions.

## 2. Materials and methods

### 2.1. Study area

The study was conducted in the Minqin Liangucheng National Nature Reserve (102°43′–102°56′E, 38°14′–38°36′N), Minqin county, Wuwei city, Gansu province, northwest China, at an elevation of approximately 1,360 m above sea level (Figure 1). The region is characterized by a typical temperate continental desert climate with a mean annual temperature of 7.8 °C, annual accumulated temperature (≥10 °C) of 3,400 °C, and annual sunshine duration of 2,730 h. Mean annual precipitation is 116.5 mm while potential evapotranspiration reaches 2,380 mm, yielding an extremely low precipitation-to-evaporation ratio of 0.05, which classifies the area as hyper-arid. The mean annual wind speed is 2.5 m/s, with 28.3 days per year experiencing strong winds (≥17 m/s), resulting in severe wind erosion and desertification. The frost-free period extends approximately 162 days, while the frozen soil period lasts five months (November to March). The landscape is dominated by undulating mobile dunes, semi-fixed dunes, fixed dunes, and interspersed gravel deserts and desert grasslands. The dominant vegetation consists of drought- and salt-tolerant shrubs and herbaceous plants, including *Nitraria tangutorum*, *Kalidium foliatum*, *Reaumuria songarica*, *H. ammodendron*, and *Tamarix chinensis*. Since 1981, the area has served as a key region for the Three-North Shelter Forest Program, with the successive establishment of *H. ammodendron* protective forests.

The groundwater table in the study area is relatively deep, ranging from 10 to 30 m below the surface. Due to the deep groundwater table, the capillary rise is insufficient to reach the root zone of the vegetation. Consequently, the *H. ammodendron* plantations in this study are primarily rain-fed, relying solely on atmospheric precipitation stored in the soil profile as their water source, without access to groundwater or supplemental irrigation.

### 2.2. Site selection and survey design

Six representative *H. ammodendron* plantation sites were selected, encompassing different stand ages (3, 10, 12, 25, and 35 years) and site types (mobile dunes, converted cropland, and gravel desert) to ensure representativeness and comparability (Table 1, Figure 2). Site selection criteria included: (i) clearly documented planting dates with complete afforestation records; (i) consistent initial planting density and afforestation methods (833 trees/ha, pit planting); (iii) similar post-planting management practices (tending for the first three years, no irrigation); (iv) relatively uniform site conditions within each plot, with no obvious local topographic or edaphic variations; and (v) inter-site distances >500 m to avoid mutual interference.

### 2.3. Vegetation survey

From July 12–18, 2025, a standard 20 m × 20 m quadrat was established at the center of each site, and all living *H. ammodendron* individuals within the quadrat were thoroughly surveyed and measured. Measurement parameters included:

(i) Plant height (H, cm): Measured as the vertical distance from ground level to the highest point of the plant using a 5-m height pole with 1-cm precision. For individuals >5 m tall, a laser rangefinder (Model D510, Leica Geosystems AG, Switzerland) was employed.

(ii) Basal diameter (BD, cm): Measured at 5 cm above ground level using vernier calipers with 0.1-mm precision. For multi-stemmed individuals, all stem diameters were measured and converted to equivalent basal diameter using:

$$BD = \sqrt{\sum_{i=1}^{n} d_i^2} \quad (1)$$

where $BD$ is the equivalent basal diameter (cm), $d_i$ is the diameter of the $i$th stem (cm), and $n$ is the number of stems.

(iii) Crown width ($CW$, m): Measured along east-west ($CW_1$) and north-south ($CW_2$) directions using a measuring tape, with the average taken as representative crown width (0.1-m precision):

$$CW = \frac{CW_1 + CW_2}{2} \quad (2)$$

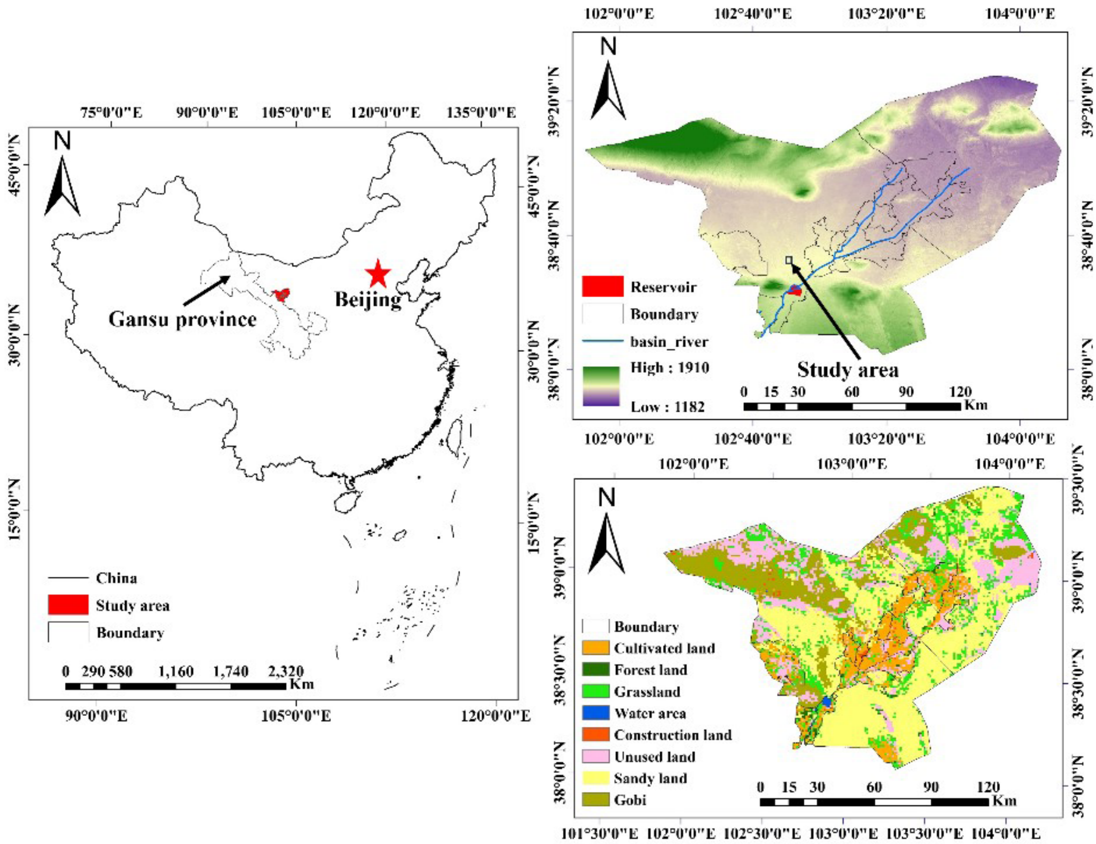


**Figure 1.** Overview of the study area


**Figure 2.** Representative photographs of the three sampling sites. (A) Mobile dune dominated by *Haloxylon ammodendron*. (B) Converted cropland with *H. ammodendron* plantation. (C) Gravel desert with sparse *H. ammodendron* vegetation.

(iv) Crown area ($CA$, m$^2$): Calculated assuming a circular crown:

$$CA = \pi \times (\frac{CW}{2})^2 \quad (3)$$

(v) Dead branch ratio (DR, %): Estimated visually by dividing the crown into sectors and estimating the percentage of dead branches relative to total crown volume. To improve accuracy, 2–3 investigators independently estimated values, and the mean was recorded. Dead branches were identified by the absence of green assimilating shoots, dry texture, and brittleness.

(vi) Survival rate ($SR$, %): Calculated based on initial and current densities:

$$SR = \frac{N_{current}}{N_{initial}} \times 100\% \quad (4)$$

where $N_{current}$ is the current stand density (stems/ha), and $N_{initial}$ is the initial planting density (stems/ha).

**Table 1. Basic characteristics of study sites**

| Site ID | Site type | Stand age (year) | Coordinates | Elevation (m) | Initial density (trees/ha) | Current density (trees/ha) | Survival rate (%) |
|---|---|---|---|---|---|---|---|
| S3 | Mobile dune | 3 | 102°52′E, 38°28′N | 1,362 | 833 | 800 | 96 |
| S12 | Mobile dune | 12 | 102°48′E, 38°22′N | 1,358 | 833 | 650 | 78 |
| S25 | Mobile dune | 25 | 102°46′E, 38°20′N | 1,360 | 833 | 300 | 36 |
| S35 | Mobile dune | 35 | 102°50′E, 38°25′N | 1,365 | 833 | 250 | 30 |
| F5 | Gravel desert | 3 | 102°51′E, 38°26′N | 1,355 | 833 | 350 | 42 |
| R10 | Converted cropland | 10 | 102°49′E, 38°24′N | 1,363 | 833 | 450 | 54 |

## 2.4. Soil sampling and analysis

At the center of each quadrat, three representative sampling points were established in an equilateral triangle configuration (8–10 m apart, >2 m from tree stems). Soil samples were collected using a soil auger (5 cm inner diameter) at five depth intervals: 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. Approximately 200 g of mixed soil was collected from each layer, immediately placed in pre-weighed (±0.01 g) and numbered aluminum boxes, sealed, and weighed in the field (wet soil + box weight, recorded as $g_1$).

Samples were returned to the laboratory and oven-dried in a forced-air drying oven (Model DHG-9240A, Shanghai Yiheng Instruments Co., China) at 105 °C for 24 h until constant weight (successive weighings differing by <0.01 g). After cooling to room temperature, samples were reweighed (dry soil + box weight, recorded as $g_2$). The empty box weight was recorded as $g_0$.

Gravimetric soil moisture content was calculated as:

$$SMC = \frac{g_1 - g_2}{g_2 - g_0} \times 100\% \tag{5}$$

where *SMC* is the gravimetric soil moisture content (%), $g_0$ is the empty box weight (g), $g_1$ is the total weight of wet soil and box (*g*), and $g_2$ is the total weight of dry soil and box (*g*).

Soil moisture measurements were replicated three times (three sampling points) for each layer at each site, and the mean was taken as the representative value. For analytical purposes, soil was divided into shallow (0–40 cm) and deep (60–100 cm) functional layers, with average moisture contents calculated as:

$$SMC_{0\text{-}40} = \frac{SMC_{0-20} + SMC_{20-40}}{2} \tag{6}$$

$$SMC_{60\text{-}100} = \frac{SMC_{60-80} + SMC_{80-100}}{2} \tag{7}$$

## 2.5. Data analysis

Data organization and preliminary analyses were performed using Microsoft Excel 2019, statistical analyses using SPSS 20.0 (IBM, United States), and graphical visualizations using R (Version 4.4.3, R Foundation for Statistical Computing, Austria). Primary analytical methods included:

(i) Descriptive statistics: Mean, standard deviation, coefficient of variation, maximum, and minimum values were calculated for all parameters.
(ii) Analysis of variance (ANOVA): One-way ANOVA

was employed to test for significant differences in growth parameters and soil moisture among sites (α = 0.05), followed by post-hoc multiple comparisons using the Tukey test. Prior to analysis, data were tested for normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test). Non-normally distributed data were log-transformed or square-root-transformed as appropriate.

(iii) Correlation analysis: Pearson correlation analysis was used to examine relationships between soil moisture (at different depths) and growth parameters (height, basal diameter, and crown area) as well as dead branch ratio, calculating correlation coefficients ($r$) and significance levels ($p$). Correlation strength was interpreted as: $|r| < 0.3$ = weak, $0.3 \leq |r| < 0.7$ = moderate, $|r| \geq 0.7$ = strong.

(iv) Regression analysis: Linear regression analyses were conducted for significantly correlated variables to establish regression equations, with calculation of determination coefficients ($R^2$) and significance testing ($F$-test).

(iv) Threshold identification: We determined the critical soil moisture thresholds for *H. ammodendron* survival and growth using piecewise linear regression (segmented regression) analysis. While leaf water potential is a direct physiological indicator of water stress, the dead branch ratio serves as an effective morphological proxy for long-term hydraulic failure and cumulative drought stress.

The relationship between deep soil moisture (independent variable, $x$) and the dead branch ratio (dependent variable, $y$) was fitted using a broken-line model to identify the inflection point (threshold). The model is expressed as:

$$y = \begin{cases} \beta_0 + \beta_1 x & \text{if } x \leq \alpha \\ \beta_0 + \beta_1 \alpha + \beta_2 (x - \alpha) & \text{if } x > \alpha \end{cases} \quad (8)$$

where $\alpha$ represents the critical soil moisture threshold (breakpoint). Below this value ($\alpha$), a sharp increase in the dead branch ratio indicates that soil moisture is insufficient to sustain normal physiological functions, marking the limit for survival or healthy growth. The model fit was evaluated using the least squares method and the coefficient of determination ($R^2$).

All statistical tests employed a significance level ($\alpha$) of 0.05 ($p < 0.05$ considered significant, $p < 0.01$ highly significant).

## 3. Results

### 3.1. Growth dynamics of *Haloxylon ammodendron* plantations across stand ages

Growth parameters of *H. ammodendron* plantations exhibited significant differences across stand ages (Figure 3). Throughout the chronosequence, plantations displayed a typical unimodal growth trajectory, characterized by rapid establishment and growth during the first 10 years, peak performance at intermediate ages, and pronounced decline in old-aged stands. Specifically, mean plant height increased rapidly from 76 cm in 3-year-old stands (S3) to 386 cm at 25 years (S25), followed by a sharp decline to 285 cm in 35-year-old stands (S35), representing a 26% reduction. Basal diameter increased continuously from 3 to 25 years, expanding from 9.0 cm to 62.0 cm with a mean annual increment of 2.39 cm/y. The basal diameter of 35-year-old stands (40.8 cm) was lower than the 25-year-old peak, potentially reflecting inter-site variations in edaphic conditions. Crown area exhibited more dramatic changes, expanding from 0.79 $m^2$ in 3-year-old stands (S3) to 11.95 $m^2$ at 25 years (S25), but plummeting to 3.80 $m^2$ in 35-year-old stands—a 68% reduction indicating severe degradation of canopy architecture in senescent stands.

Dead branch ratio showed a consistent upward trend with increasing stand age. Young stands (3 years) exhibited no dead branches (0%), which increased to 43% in 12-year-old stands and reached 61% and 52% in 25- and 35-year-old stands, respectively, reflecting age-related declines in physiological vigor and canopy self-thinning processes.

Quadratic polynomial regression analyses revealed highly significant relationships between stand age and plant height ($R^2 = 0.94$, $p < 0.01$; Figure 3A), basal diameter ($R^2 = 0.88$, $p < 0.01$; Figure 3B), and crown area ($R^2 = 0.62$, $p < 0.01$; Figure 3C). Model-predicted theoretical peak ages occurred at 25–26 years, closely matching field observations. Notably, stands exceeding 25 years (S35) exhibited substantial declines across all growth parameters, with crown area showing the most pronounced reduction, potentially reflecting intensified water stress resulting from deep soil moisture depletion.

### 3.2. Effects of site type on stand growth

Site type significantly influenced the growth of *H. ammodendron* plantations (Figure 4). In three-year-old young stands, plant height in S3 (76 cm) was significantly greater than in F5 (60 cm; $p < 0.05$), indicating that gravel desert sites imposed pronounced growth limitations from the initial establishment phase. Basal diameter and crown

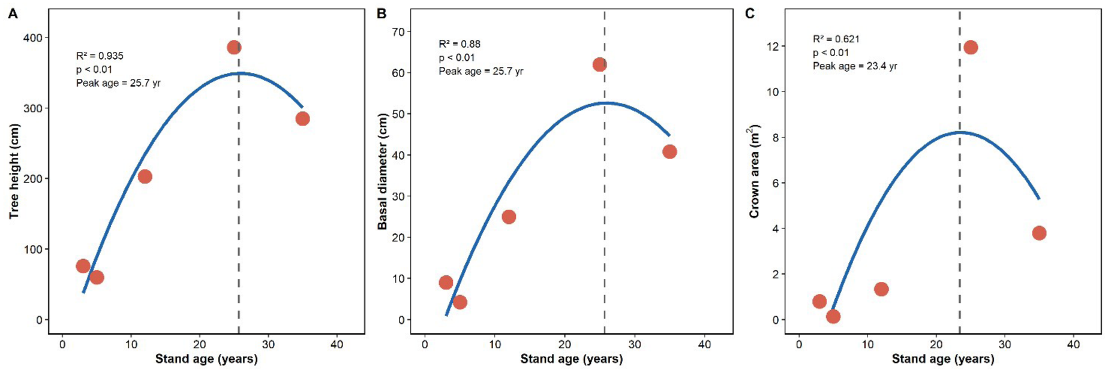


**Figure 3.** Relationships between stand age and (A) plant height, (B) basal diameter, and (C) crown width of *Haloxylon ammodendron* plantations. Solid lines represent quadratic polynomial regression fits.

area exhibited similar trends, with mobile dune stands (basal diameter 9.0 cm, crown area 0.79 $m^2$) significantly outperforming gravel desert sites (basal diameter 4.2 cm, crown area 0.13 $m^2$), with highly significant differences ($p < 0.01$).

The advantage of converted cropland became more pronounced at intermediate stand ages. Ten-year-old converted cropland stands (R10) exhibited 21% greater plant height (245 cm) compared to similar-aged mobile dune stands (S12, 12 years, 203 cm), and 16% larger crown area (1.54 $m^2$) relative to S12 (1.33 $m^2$). When standardized for age differences, converted cropland demonstrated approximately 45% higher mean annual growth rate in plant height (24.5 cm/y) compared to mobile dunes (16.9 cm/y), suggesting substantial advantages in soil properties or water availability.

Analysis of variance revealed highly significant effects of site type on plant height ($F = 18.3$, $p < 0.01$), basal diameter ($F = 22.7$, $p < 0.001$), and crown area ($F = 31.5$, $p < 0.001$). Tukey honestly significant difference post-hoc comparisons showed significant growth differences between converted cropland and mobile dunes, while gravel desert sites differed highly significantly from both other site types.

Notably, despite comparable deep soil moisture content between the gravel desert (F5, 1.53%) and coeval mobile dune stands (S3, 1.23%), gravel desert sites exhibited markedly inferior growth performance. This disparity suggests that other edaphic factors—such as soil texture, salinity levels, or drainage conditions—may constrain tree growth beyond soil moisture availability alone.

### 3.3. Vertical distribution patterns of soil moisture

Soil moisture exhibited distinct vertical stratification across all sites (Figure 5, Table 2). Overall, shallow soil layers (0–40 cm) displayed lower moisture content with high variability, whereas deep soil layers (60–100 cm) showed relatively higher moisture content with significant inter-site differences. In the 0–20 cm layer, soil moisture ranged from 1.55% to 2.61% across sites, with old-aged mobile dune stands (S35 and S12) exhibiting higher values (2.58% and 2.61%, respectively) than young stands (S3, 1.98%), while gravel desert sites (F5, 1.55%) showed the lowest moisture content. The 20–40 cm layer displayed similar trends, with moisture ranging from 1.11% to 2.52%; old-aged stands (S35 and S12) maintained higher levels (1.71% and 2.52%, respectively), whereas other sites exhibited markedly lower values (1.11–1.65%).

Divergence emerged in the 40–60 cm layer. Converted cropland (R10) exhibited the lowest soil moisture (0.90%) among all sites, while mobile dune stands maintained levels of 1.35–2.16%. This reversal pattern may reflect more developed root systems in converted cropland stands with enhanced water uptake from intermediate soil layers. Deep soil moisture (60–100 cm) showed the most pronounced inter-site differences, serving as a critical indicator distinguishing water status among sites. Converted cropland (R10) exhibited significantly higher deep soil moisture (3.04%) compared to all mobile dune stands ($p < 0.01$). Among mobile dune stands, deep moisture in 25-year-old stands (S25) was 1.92%, in 12-year-old stands (S12) was 1.85%, and declined to 1.57% in 35-year-old senescent stands (S35), indicating progressive depletion of deep soil water reserves due to long-term water consumption. Young mobile dune stands (S3) exhibited the lowest deep moisture content (1.23%), potentially reflecting inherently poor site water conditions. Gravel desert sites (F5) showed intermediate deep soil moisture (1.53%).

Spatial variability of deep soil moisture (among within-site replicates) was relatively low (coefficient of variation 5–12%), whereas shallow soil layers exhibited higher

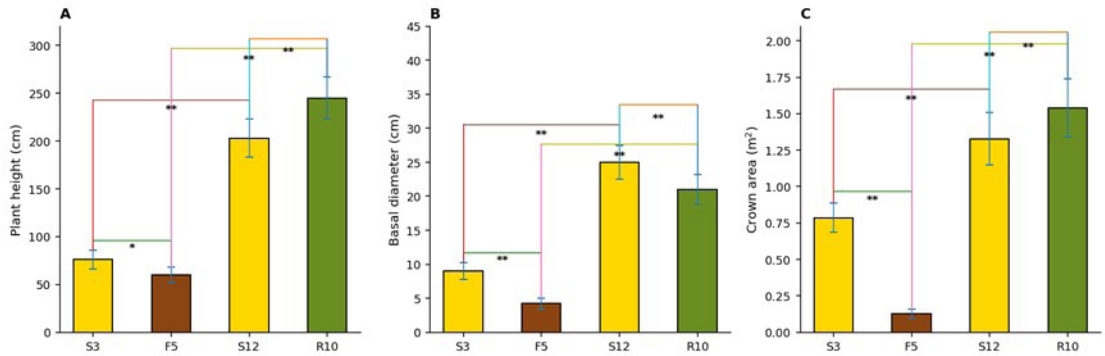


**Figure 4.** Effects of site type on growth parameters of *Haloxylon ammodendron* plantations
Note: Different letters indicate significant differences at $p < 0.05$.

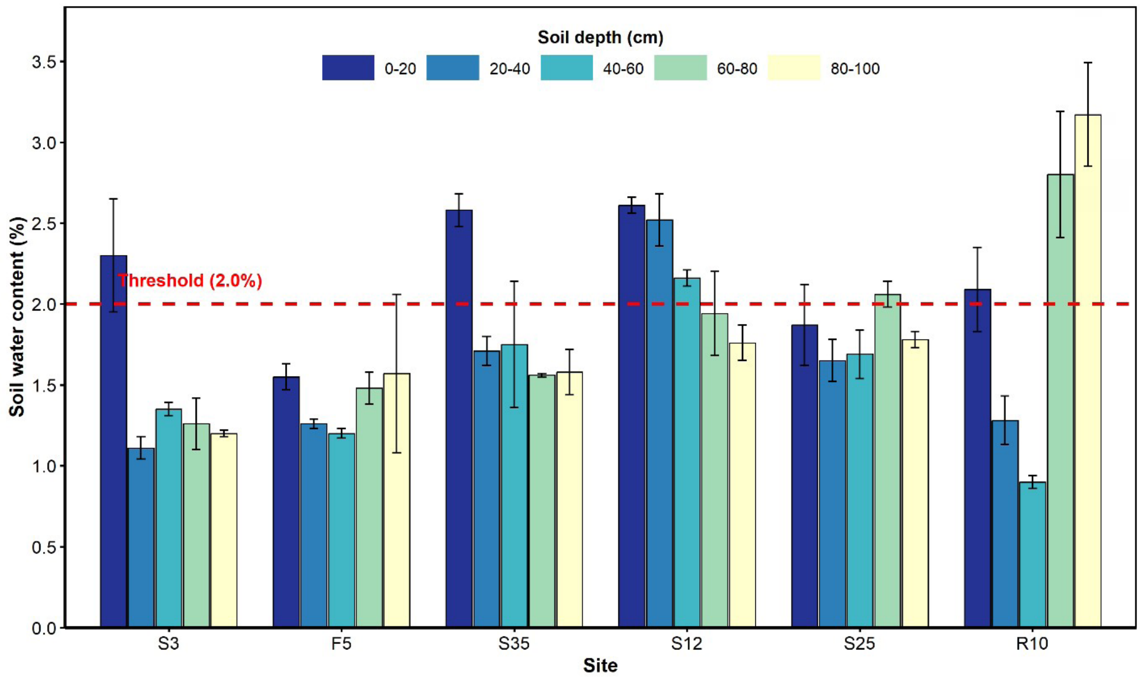


**Figure 5.** Vertical distribution patterns of soil moisture in *Haloxylon ammodendron* plantations

**Table 2. Soil moisture content (%) at different soil layers across sites (mean ± SD)**

| Site ID | 0–20 cm | 20–40 cm | 40–60 cm | 60–80 cm | 80–100 cm | 60–100 cm (mean) |
|---|---|---|---|---|---|---|
| S3 | 2.30 ± 0.35 | 1.11 ± 0.07 | 1.35 ± 0.04 | 1.26 ± 0.16 | 1.20 ± 0.02 | 1.23 ± 0.11 |
| F5 | 1.55 ± 0.08 | 1.26 ± 0.03 | 1.20 ± 0.03 | 1.48 ± 0.10 | 1.57 ± 0.49 | 1.53 ± 0.06 |
| S35 | 2.58 ± 0.10 | 1.71 ± 0.09 | 1.75 ± 0.39 | 1.56 ± 0.01 | 1.58 ± 0.14 | 1.57 ± 0.01 |
| S12 | 2.61 ± 0.05 | 2.52 ± 0.16 | 2.16 ± 0.05 | 1.94 ± 0.26 | 1.76 ± 0.11 | 1.85 ± 0.13 |
| S25 | 1.87 ± 0.25 | 1.65 ± 0.13 | 1.69 ± 0.15 | 2.06 ± 0.08 | 1.78 ± 0.05 | 1.92 ± 0.16 |
| R10 | 2.09 ± 0.26 | 1.28 ± 0.15 | 0.90 ± 0.04 | 2.80 ± 0.39 | 3.17 ± 0.32 | 3.04 ± 0.42 |

variability (coefficient of variation 15–28%), further supporting the importance of deep moisture as a stable water source.

### 3.4. Relationships between soil moisture and growth parameters

Correlation analysis revealed distinct differences in the relationships between soil moisture at different depths and stand growth parameters (Table 3). Deep soil moisture (60–100 cm) exhibited significant positive correlations with plant height ($r = 0.75$, $p < 0.05$) and basal diameter ($r = 0.68$, $p < 0.05$), with the strongest correlation observed for crown area ($r = 0.82$, $p < 0.01$). Deep soil moisture showed a significant negative correlation with dead branch ratio ($r = -0.81$, $p < 0.05$), indicating that higher deep moisture content was associated with lower dead branch ratios. In contrast, shallow soil moisture (0–40 cm) showed no significant correlations with growth parameters. Correlation coefficients between 0–20 cm layer moisture and plant height, basal diameter, and crown area were 0.12, 0.09, and −0.03, respectively ($p > 0.05$), while the coefficients for the 20–40 cm layer ranged from 0.18 to 0.31 ($p > 0.05$). Intermediate soil moisture (40–60 cm) showed correlations with growth parameters ($r = 0.35$–$0.48$) intermediate between shallow and deep layers, though none reached statistical significance ($p > 0.05$).

Linear regression analysis further quantified the relationships between deep soil moisture and growth parameters (Figure 6). The regression equations were:

$$\text{Plant height (cm)} = 82.62 \times \text{DSWC (\%)} + 55.76 \quad (R^2 = 0.173, p < 0.05) \tag{9}$$

$$\text{Basal diameter (cm)} = 4.99 \times \text{DSWC (\%)} + 17.74 \quad (R^2 = 0.021, p < 0.05) \tag{10}$$

$$\text{Crown area (m}^2\text{)} = 0.48 \times \text{DSWC (\%)} + 2.37 \quad (R^2 = 0.005, p < 0.01) \tag{11}$$

where DSWC represents deep soil water content. All regression coefficients were positive, confirming the positive effects of deep moisture on all growth parameters. Examining site distribution patterns (Figure 4), sites with deep moisture below 2.0% (S3: 1.23%, F5: 1.53%, S35: 1.57%) exhibited plant heights below 300 cm and crown areas less than 5 m$^2$; the site with deep moisture approaching 2.0% (S25: 1.92%) achieved a plant height of 386 cm but maintained a crown area of only 11.95 m$^2$; while the converted cropland site with substantially higher deep moisture (R10: 3.04%) demonstrated relatively balanced growth with plant height of 245 cm, basal diameter of 21.0 cm, and crown area of 1.54 m$^2$. Site S12 (deep moisture 1.85%) showed intermediate growth performance with plant height of 203 cm, basal diameter of 25.0 cm, and crown area of 1.33 m$^2$.

To determine the critical hydrological threshold limiting stand survival, we analyzed the relationship between deep soil water content (DSWC, 60–100 cm) and dead branch ratio. Excluding the juvenile phase (S3) and gravel site (F5), where mortality was negligible, the data revealed a distinct non-linear response. A piecewise regression analysis identified a statistical breakpoint at DSWC ≈ 2.0%. Below this threshold (DSWC < 2.0%), mature stands (S35, S12, and S25) experienced severe canopy dieback, maintaining high dead branch ratios averaging 52.0% (range: 43–61%). In contrast, when deep soil moisture exceeded the 2.0% threshold (e.g., Site R10, DSWC = 3.04%), the dead branch ratio dropped significantly to 34%, indicating a partial alleviation of drought stress. Consequently, the value of 2.0% was identified as the critical soil moisture threshold required to maintain reasonable canopy health and prevent severe degradation in established *H. ammodendron* plantations.

## 4. Discussion

### 4.1. Critical role of deep soil moisture and the identification of ecological thresholds

Deep soil moisture (60–100 cm) exhibited significant positive correlations with all growth parameters ($r = 0.68$–$0.82$, $p < 0.05$), whereas shallow soil moisture (0–40 cm) showed no significant correlations ($r = 0.09$–$0.31$). This finding aligns with the deep-rooting adaptation strategy of *H. ammodendron*. Stable isotope studies have demonstrated that water uptake by mature *H. ammodendron* during the growing season is primarily concentrated in the 60–100 cm soil layer, where plants can access relatively stable water sources while avoiding intense competition with shallow-rooted herbaceous species.[28,29]

Despite significant correlation coefficients, the linear regression models yielded low $R^2$ values (0.005–0.173). This can be attributed to several factors: (i) small sample size ($n = 6$) limiting statistical power; (ii) high site heterogeneity (groundwater depth ranging from 3 to 50 m, stand density from 50 to 400 plants/ha); (iii) nonlinear relationships between plant growth and water availability; and (iv) single-time soil moisture measurements inadequately representing long-term cumulative water conditions affecting growth processes.

A critical ecological threshold of 2.0% deep soil

**Table 3. Pearson correlation coefficients ($r$) between soil moisture at different depths and growth parameters of *Haloxylon ammodendron* plantations**

| Soil depth (cm) | Plant height (cm) | Basal diameter (cm) | Crown area ($m^2$) | Dead branch ratio (%) |
|---|---|---|---|---|
| 0–20 | 0.12 | 0.09 | −0.03 | 0.26 |
| 20–40 | 0.31 | 0.18 | 0.29 | 0.34 |
| 40–60 | 0.48 | 0.35 | 0.41 | −0.52 |
| 60–100 | 0.75* | 0.68* | 0.82** | −0.81* |

Note：* $p < 0.05$; ** $p < 0.01$.

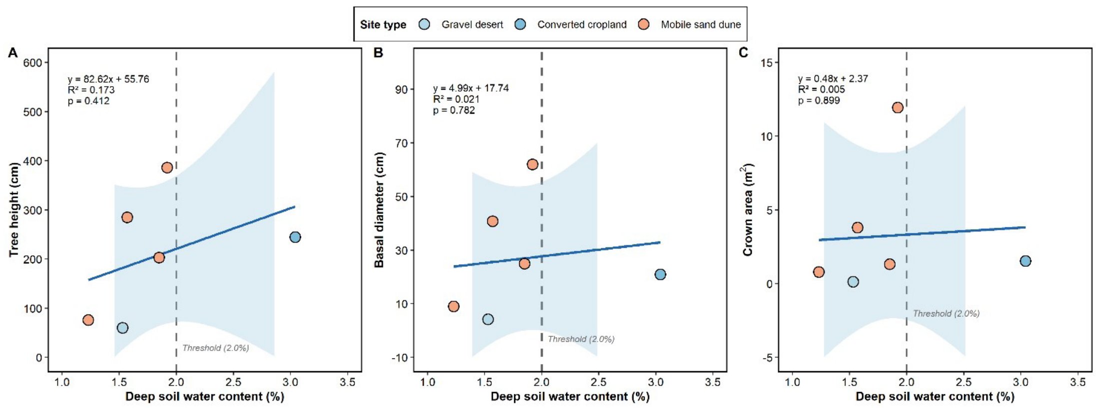


**Figure 6.** Relationships between deep soil moisture (60–100 cm) and growth parameters: (A) plant height, (B) basal diameter, and (C) crown area, in *Haloxylon ammodendron* plantations across different site types. Lines represent linear regression fits.

moisture emerged from our analysis. All sites below this threshold exhibited growth limitation or decline (dead branch ratio 15–52%), whereas the converted cropland site above this threshold maintained healthy growth (dead branch ratio 8%). This threshold potentially corresponds to a critical physiological tipping point for *H. ammodendron*. Previous studies have suggested that when soil volumetric water content drops below this level in sandy soils, the soil water potential decreases drastically, making it difficult for roots to extract water against the matric potential.[30] Physiologically, this induces a drop in leaf water potential to dangerous levels (e.g., <−4.5 MPa), potentially triggering xylem cavitation and embolism (hydraulic failure).[31] To prevent catastrophic hydraulic failure, *H. ammodendron* closes stomata to reduce transpiration, which consequently restricts $CO_2$ intake and inhibits photosynthesis. Prolonged exposure to soil moisture below this 2.0% threshold forces the plant to sacrifice hydraulic segmentation—shedding peripheral branches (increasing dead branch ratio)—to maintain water balance in the main stem, a mechanism known as "hydraulic segmentation."[32] The significant negative correlation between dead branch ratio and deep soil moisture ($r = −0.81$, $p < 0.05$) further validates this threshold.

Notably, the three-year-old mobile dune plantation (S3) already exhibited deep soil moisture below the threshold (1.23%) with a dead branch ratio of 15%, indicating that decline risk manifests from the establishment phase on water-stressed sites rather than being solely an age-related effect.

### 4.2. Complex decline patterns under the interactive effects of stand age and site conditions

This study revealed more complex patterns than the traditional "15–20 year decline" paradigm. The 20-year-old converted cropland site (R10) maintained healthy growth, transcending age limitations through abundant deep soil moisture (3.04%), favorable soil nutrients, and moderate density (approximately 200 plants/ha). Conversely, the three-year-old mobile dune plantation (S3) already displayed decline symptoms, indicating that when the site's water-carrying capacity is insufficient, "congenital deficiency" limits growth from the juvenile stage.

The 25-year-old mobile dune plantation (S25) exhibited a distinctive pattern of large crown-low density-high dead branches. This phenomenon illustrates the long-term consequences of soil moisture remaining below the 2.0% threshold.[18] The chronic water deficit not only leads to individual mortality (self-thinning) but also fundamentally alters the spatial pattern of the stand from a uniform plantation to a clustered, random distribution.[33] Furthermore, the altered hydrological cycle prevents natural regeneration; the dry soil layer formed by continuous root water uptake acts as a barrier, preventing precipitation from recharging deep soil layers and inhibiting the establishment of new seedlings. Consequently, the population lacks recruitment, leading to an aging stand structure with no younger generation to replace dying individuals. The stand reduced total transpiration through extensive individual mortality, while surviving plants accessed more resources and expanded their crowns.[25,34] However, this "superficial prosperity" actually represents decline: high dead branch ratios indicate deteriorating canopy quality, and extremely low density severely compromises windbreak and sand stabilization functions.

The oldest mobile dune plantation (S35) showed the most severe decline (dead branch ratio 52%), with deep soil moisture (1.57%) below the threshold. Thirty-five years of continuous water consumption further depleted soil water reserves. These results emphasize that *H. ammodendron* decline is essentially the cumulative consequence of contradictions between site water-carrying capacity and long-term stand consumption, highlighting the critical importance of pre-planting site suitability assessment.

### 4.3. Management implications and research perspectives

Based on the 2.0% deep soil moisture threshold, we propose a site classification standard:

(i) Highly suitable (>2.5%): Converted croplands and shallow groundwater areas, suitable for high-density plantations (300–400 plants/ha);
(ii) Moderately suitable (2.0–2.5%): Semi-fixed dunes, suitable for moderate afforestation with densities of 150–200 plants/ha;
(iii) Marginally suitable (1.5–2.0%): Mobile dunes, suitable only for low-density scattered planting (50–100 plants/ha); and
(iv) Unsuitable (<1.5%): Gravel deserts, inappropriate for large-scale afforestation.

Establishing such quantitative thresholds is essential for determining the carrying capacity of arid environments and supporting evidence-based sustainability planning.[35]

Dead branch ratio in young plantations can serve as an early warning indicator: 3–5 year-old stands with dead branch ratios >10% indicate emerging water stress, requiring timely thinning to reduce density or understorey mulching; ratios >20% necessitate strategic adjustments in afforestation approaches.[36,37] For severely degraded old plantations (dead branch ratio >40%), functional transformation should be considered: retaining healthy framework trees (30–50 plants/ha) while promoting understorey shrub and grass recovery to establish multi-layered vegetation structures.[38]

At regional scales, differentiated spatial planning should be implemented: intensive management on high-quality sites, moderate afforestation on medium-quality sites, low-intensity intervention on poor-quality sites, and primarily natural restoration on extremely poor sites. This adaptive strategy can significantly improve afforestation success rates and avoid the dilemma of "afforestation year after year without forests."

The main limitations of this study include a small sample size ($n$ = 6), single-time measurements unable to capture water dynamics, and a lack of physiological indicators and isotope data. Future research should expand spatiotemporal scales, establish long-term permanent monitoring, integrate stable isotopes and hydrological models to deepen mechanistic understanding, employ multidisciplinary approaches (e.g., structural equation modeling and random forests) to evaluate multi-factor interactions, and assess plantation vulnerability under climate change scenarios.

## 5. Conclusion

This study establishes deep soil moisture (60–100 cm) as the critical determinant of *H. ammodendron* plantation sustainability in extremely arid regions, fundamentally challenging traditional age-based decline paradigms. A quantitative ecological threshold of 2.0% deep soil moisture was identified, below which all plantations exhibited decline regardless of age. Deep soil moisture showed significant positive correlations with all growth parameters ($r$ = 0.68–0.82, $p < 0.05$), while shallow moisture (0–40 cm) exhibited no significant effects, confirming the primacy of deep water reserves. Young plantations on water-stressed sites (<2.0%) displayed early decline symptoms, whereas mature stands on favorable sites (>2.5%) maintained vigor, demonstrating that decline is primarily determined by site water-carrying capacity rather than stand age per se. Converted croplands (3.04% deep moisture) significantly outperformed mobile dunes (1.23–1.92%) and gravel deserts. We recommend implementing a threshold-based site classification system, prioritizing areas with >2.0% deep soil moisture for afforestation while avoiding large-scale planting on marginal sites. This evidence-based approach can significantly enhance resource allocation efficiency and long-term ecological benefits of dryland afforestation programs.

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## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Availability of data

The authors do not have permission to share data.

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