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Deep Soil Desiccation and Root Distribution in Strip-Planted *Caragana korshinskii* Woodland in the Loess Hilly Region (Postprint)

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Abstract

In response to limited research on root systems, soil moisture characteristics, and deep soil desiccation in strip plantations of Caragana korshinskii in the Loess Hilly Region, this study investigated 20-year rain-fed strip plantations of Caragana korshinskii in the mountainous areas of southern Ningxia, with similar dryland farmland as a control, analyzing soil moisture at depths of 0–1000 cm, vertical distribution of Caragana korshinskii roots, and their correlations. The results showed that: (1) The 20-year Caragana korshinskii plantation exhibited soil desiccation at depths of 0–1000 cm, with soil moisture content both within and between strips being lower than that in farmland; soil moisture content within strips decreased by 1.46% compared to that between strips in the 0–1000 cm soil layer. (2) Within the 300–1000 cm soil layer, the 20-year Caragana korshinskii plantation exhibited varying degrees of deficit and desiccation, with water availability values of 0.21 and 0.02 between and within strips, respectively, and average water supply coefficients of 0.49 and 0.33, respectively. (3) The root system of Caragana korshinskii plantations was mainly concentrated in the 0–80 cm soil layer, where root dry weight between and within strips accounted for 46.33% and 45.56% of total root weight, respectively, root surface area density accounted for 66.58% and 63.51% of total root surface area density, respectively, and root length density accounted for 59.54% and 58.45% of total root length density, respectively. This study provides valuable insights for the in-depth understanding of root systems and water in artificial Caragana korshinskii plantations in semi-arid loess regions.

Full Text

Preamble

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Deep Soil Desiccation and Root Distribution of Belted Caragana korshinskii Forest in Loess Hilly Region

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Abstract: Research on root systems, soil moisture characteristics, and deep soil desiccation in artificial Caragana korshinskii forests remains limited in the loess hilly region. This study investigated a 20-year-old rainfed strip-planted C. korshinskii forest in southern Ningxia mountainous area, using a similar dryland farmland as control. Soil moisture content (0–1000 cm depth), vertical root distribution, and their correlations were analyzed. The results revealed: (1) Deep soil desiccation occurred throughout the 0–1000 cm profile in the C. korshinskii forest, with soil moisture content in both intra-band and inter-band positions significantly lower than farmland. Soil moisture availability was 0.21 for inter-band and 0.02 for intra-band positions, with average water supply coefficients of 0.49 and 0.33, respectively. (2) The 20-year artificial C. korshinskii forest exhibited varying degrees of water deficit and desiccation. Water availability in intra-band positions was 1.46% lower than inter-band positions across the 0–1000 cm profile. (3) C. korshinskii roots concentrated primarily in the 0–80 cm layer, where root dry weight accounted for 45.56% (intra-band) and 46.33% (inter-band) of total root weight, root length density comprised 58.45% (intra-band) and 59.54% (inter-band) of the total, and root surface area density represented 63.51% (intra-band) and 66.58% (inter-band) of the total. These findings provide valuable insights for sustainable vegetation restoration, soil water utilization efficiency, and artificial vegetation establishment in semi-arid loess regions.

Keywords: Caragana korshinskii forest; soil moisture availability; soil drying degree; root distribution

1.1 Study Area Overview

The experimental site is located in Wangwa Town, Pengyang County, Guyuan City, southern Ningxia mountainous area (36°17 25 N, 106°39 42 E). The region has a mean annual temperature of 8.6°C, mean annual precipitation of 480 mm, annual sunshine duration of 2590 h, and a frost-free period of 150 days. The soil type is loessal soil (Cumuli-Orthic Anthrosol) with a mean bulk density of 1.33 $g \cdot cm^{-3}$ in the 0–300 cm layer. Soil texture is silt loam, with average silt, sand, and clay contents of 72.69%, 19.36%, and 7.95%, respectively. The permanent wilting point is 7.12% (determined using the Van Genuchten model), and field capacity is 19.36% (measured value). Natural vegetation transitions from shrub steppe to typical steppe, dominated by low-growing grasses with sparse shrubs. Primary artificial vegetation includes Caragana korshinskii, alfalfa (Medicago sativa), mountain peach (Amygdalus davidiana), and Mongolian pine (Pinus sylvestris var. mongolica).

1.2 Research Methods

Uniform 20-year-old artificial strip-planted C. korshinskii forests on mid-slope positions were selected as experimental plots, with a dryland farmland (approximately 120 m away, similar slope and aspect) serving as control. The farmland crops were foxtail millet (Setaria italica) and maize (Zea mays). A 500 cm × 500 cm quadrat was established with the C. korshinskii strip as one boundary, replicated three times. Soil moisture and root sampling were conducted at three positions: intra-band (within the strip), inter-band (between strips), and farmland center (Figure 1). The study area featured a planting pattern of one row per strip with 100 cm spacing between strips. C. korshinskii averaged 1.6 m in height, with inter-band vegetation dominated by Stipa grandis (Poaceae). Sampling points were located at the center between wide and narrow rows.

[Figure 1: see original paper]

Figure 1 Sampling plot distribution in the study area

1.3 Methodological Framework

1.3.1 Soil Water Deficit Degree

Soil water deficit degree (K) quantifies water deficiency for plant growth, calculated following Chen et al. [**?**]:

$$K = \frac{\theta_f - \theta}{\theta_f - \theta_w} \times 100\%$$

where K is soil water deficit degree (%), is actual soil water content (%), _f is field capacity (%), and _w is wilting point (%). When K = 0, no water deficit exists. Deficit levels are classified as: K < 30% (no deficit), 30% ≤ K < 60% (mild deficit), 60% ≤ K < 90% (moderate deficit), and K ≥ 90% (severe deficit).

1.3.2 Soil Water Availability

Soil water availability index (A) represents the ratio of actual available water to maximum available water, indicating the degree to which vegetation can utilize soil moisture:

$$A = \frac{\theta - \theta_w}{\theta_f - \theta_w}$$

where A is soil water availability index (dimensionless),   is actual soil water content (%), _f is field capacity (%), and _w is wilting point (%). Higher A values indicate greater water availability for vegetation; A $\leq$ 0 indicates unavailable water. Availability is classified into five levels (Table 1).

Table 1 Evaluation index of soil water availability

Availability Level	Soil Moisture Range (%)	Description
>19.36	80–100% of field capacity	Surplus water
15.49–19.36	60–80% of field capacity	Easily available water
11.62–15.49	40–60% of field capacity	Moderately available water
7.12–11.62	Wilting point to 40% of field capacity	Hard-to-use water
<7.12	Below wilting point	Unavailable water

1.3.3 Soil Desiccation Intensity

Soil desiccation intensity index (I_{SD}) quantifies drying degree:

$$I_{SD} = \frac{\theta_s - \theta}{\theta_s - \theta_w} \times 100\%$$

where I_{SD} is soil desiccation index (%),   is actual soil moisture (%), _s is stable soil moisture (%), and _w is wilting point (%). Following Li et al. [?] and considering our data range, desiccation is classified as: I_{SD} $\geq$ 100% (extreme desiccation), 75% $\leq$ I_{SD} < 100% (severe desiccation), 50% $\leq$ I_{SD} < 75% (moderate desiccation), and I_{SD} < 50% (mild/no desiccation).

1.3.4 Root Length Density

Root length density (RLD) is calculated as:

$$RLD = \frac{RL}{V}$$

where RLD is root length density ($cm \cdot cm^{-3}$), RL is root length (cm), and V is root drill volume (cm^3).

1.3.5 Root Surface Area Density

Root surface area density (RSD) is calculated as:

$$RSD = \frac{RS}{V}$$

where RSD is root surface area density ($cm^2 \cdot cm^{-3}$), RS is root surface area (cm^2), and V is root drill volume (cm^3).

1.4 Data Analysis

Soil moisture content, root length density, root surface area density, and other parameters were calculated and processed using Microsoft Excel 2010. SPSS 26.0 was used for one-way ANOVA and significance testing. Origin 2018 was used for graphical visualization. Standard errors were calculated for all data.

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2 Results and Analysis

2.1 Soil Moisture Characteristics

2.1.1 Vertical Distribution of Soil Moisture (0–1000 cm) Soil moisture content in both intra-band and inter-band positions of C. korshinskii forest showed a decreasing-then-increasing trend with depth (Figure 2). Moisture content was consistently lower than farmland at all depths. Inter-band and intra-band moisture contents intersected at 880 cm, with inter-band moisture being superior to intra-band. In the 0–40 cm layer, average moisture content in inter-band and intra-band positions was 27.60% and 46.09% lower than farmland, respectively. In the 40–280 cm layer, reductions were 14.78% and 33.39%, showing a sharp decline. In the 280–440 cm layer, reductions were 47.40% and 71.67%, with a gradual decreasing trend. In the 440–800 cm layer, reductions were 63.25% and 67.85%, showing fluctuation. In the 800–1000 cm layer, reductions were 52.25% and 50.58%, with an upward trend. Across the entire 0–1000 cm profile, average moisture contents were 7.77% (inter-band) and 6.31% (intra-band).

[Figure 2: see original paper]

Figure 2 Vertical distribution of soil water content in Caragana korshinskii forest land and farmland

2.1.2 Soil Water Deficit Degree (300–1000 cm) Soil water deficit degree is a critical indicator of moisture status and profile distribution. Using nearby farmland as the baseline, the water deficit index of C. korshinskii forest was analyzed. The 0–300 cm layer was excluded due to high rainfall and surface vegetation influence, as well as partial recovery from precipitation. Table 2 shows that soil water deficit degree decreased with depth: 300–440 cm (moderate deficit), 440–800 cm (mild deficit), and 800–1000 cm (no deficit). The 300–1000 cm layer stored 57.61% (inter-band) and 47.10% (inter-band) of farmland water storage, respectively.

Table 2 Soil water storage deficit of Caragana korshinskii forest and farmland in 300–1000 cm soil layer

Depth (cm)	Average Soil Moisture (%)	Water Storage (mm)	Deficit Degree (%)
300–440	6.16b	46.79a	38.72a
440–800	7.09b	12.77b	32.79c
800–1000	10.09a	16.48a	-0.84a

Note: Different lowercase letters indicate significant differences ($P < 0.05$). Same below.

2.1.3 Soil Water Availability and Supply Coefficient Soil water availability classification showed that intra-band positions had hard-to-use water at 0–360 cm and unavailable water at 640–1000 cm. Inter-band positions had moderately available water at 0–240 cm, easily available water at 240–520 cm, surplus water at 520–600 cm, and hard-to-use water at 800–1000 cm. Farmland had moderately available water at 0–40 cm, easily available water at 40–120 cm, and hard-to-use water at 360–720 cm. This indicates generally poor water availability in C. korshinskii forest.

Comparing intra-band and inter-band positions (Table 3), inter-band water availability was significantly greater than intra-band. The 840–1000 cm layer showed significantly lower availability than 0–20 cm and 200–840 cm layers ($P < 0.05$). The water supply coefficient was consistently higher in inter-band than intra-band positions, with average values of 0.49 (inter-band) and 0.33 (intra-band), indicating better water status in inter-band positions.

Table 3 Soil water availability and water supply coefficient in Caragana korshinskii forest land

<table>
<tr><th>Depth (cm)</th><th>Water Availability (Inter-band)</th><th>Water Availability (Intra-band)</th><th>Supply Coefficient (Inter-band)</th><th>Supply Coefficient (Intra-band)</th></tr>
<tr><td>0–80</td><td colspan="4">0.67$±0.47a|0.26±0.11a|0.38±0.26ab|0.14±0.07ab||80–200|0.38±0.26ab|0.14±0.07ab|0.02±0.08bc|−0.23±0.08c||200–440|0.14±0.07ab|0.02±0.08bc|−0.12±0.13c| −0.14±0.08c||440–840|0.13±0.09bc|0.06±0.08b|−0.14±0.08c| −0.14±0.08c||840–1000|0.02±0.08bc|−0.23±0.08c| −0.12±0.13c| −0.14±$0.08c</td></tr>
</table>

[Figure 3: see original paper]

Figure 3 Soil water availability of vertical profile between Caragana korshinskii forest and farmland

2.1.4 Soil Desiccation Degree Soil moisture content in both intra-band and inter-band positions of C. korshinskii forest was lower than stable moisture content throughout 300–1000 cm, indicating desiccation (Figure 4). The 0–300 cm layer was considered the active moisture zone due to rainfall infiltration effects. Average moisture contents were 6.53% (inter-band) and 5.46% (intra-band). The average desiccation index for 300–1000 cm was -0.37% (inter-band) and -0.13% (intra-band), indicating extreme desiccation. Extreme desiccation layers reached 320 cm (inter-band) and 500 cm (intra-band), with severe desiccation layers at 380 cm (inter-band) and 200 cm (intra-band). No mild or no-desiccation layers were observed within 1000 cm, suggesting limited plant-available water and poor recovery potential.

[Figure 4: see original paper]

Figure 4 Vertical distribution of soil drying degree in Caragana korshinskii forest and farmland

Table 4 Soil drying degree in 300–1000 cm soil layer in the intra-band and inter-band of Caragana korshinskii forest

Position	Average Desiccation Index	Desiccation Intensity	Extreme Layer (cm)	Severe Layer (cm)
Inter-band	-0.37	Extreme	320	380
Intra-band	-0.13	Extreme	500	200

2.2 Root Distribution Characteristics

2.2.1 Vertical Distribution of Root Dry Weight Root dry weight in both intra-band and inter-band positions decreased significantly with depth (Table 5). Root dry weight was higher intra-band than inter-band in the 0–160 cm layer. No roots were found below 840 cm in inter-band positions, while intra-band roots extended to 880 cm. In the 0–80 cm layer, root dry weights were 1383.36 $g \cdot m^{-3}$ (inter-band) and 1397.19 $g \cdot m^{-3}$ (intra-band), accounting for 46.33% and 45.56% of total root weight, respectively. This indicates root enrichment in surface layers. Root dry weight in 80–200 cm was 835.99 $g \cdot m^{-3}$ (inter-band) and 871.22 $g \cdot m^{-3}$ (intra-band), representing 28.00% and 28.41% of totals. In 200–440 cm, values were 577.23 $g \cdot m^{-3}$ and 583.00 $g \cdot m^{-3}$ (19.33% and 19.01%). In 440–840 cm, values were 189.43 $g \cdot m^{-3}$ and 189.09 $g \cdot m^{-3}$ (6.34% and 6.18%). No roots were observed in 840–1000 cm (inter-band), while intra-band had minimal roots (26.00 $g \cdot m^{-3}$). Total root dry weight averaged 119.43 $g \cdot m^{-3}$ (inter-band) and 122.70 $g \cdot m^{-3}$ (intra-band). The inverse relationship between root distribution and soil moisture content confirms that greater root density increases water consumption and reduces soil moisture.

Table 5 Root dry weight in Caragana korshinskii forest land

Depth (cm)	Inter-band ($g \cdot m^{-3}$)	% of Total	Intra-band ($g \cdot m^{-3}$)	% of Total
0–80	1383.36a	46.33	1397.19a	45.56
80–200	835.99b	28.00	871.22b	28.41
200–440	577.23c	19.33	583.00c	19.01
440–840	189.09d	6.34	189.43d	6.18
840–1000	0d	0	26.00e	0.84

2.2.2 Vertical Distribution of Root Surface Area Density Total root surface area density was significantly greater intra-band than inter-band ($P < 0.05$). Root surface area density ranged from 0.25–3.55 $cm^2 \cdot cm^{-3}$ (intra-band) and 0.26–2.51 $cm^2 \cdot cm^{-3}$ (inter-band) across 0–1000 cm. The maximum occurred in the 0–80 cm layer, accounting for 66.58% (intra-band) and 63.51% (inter-band) of the total. The 80–200 cm layer represented 17.51% and 16.07% of totals, while 200–440 cm contributed 11.01% and 13.27%. Minimal root surface area was observed below 440 cm. The discrepancy between intra-band root surface area density and soil moisture indicates that higher root density increases water absorption, reducing soil moisture content.

[Figure 5: see original paper]

Figure 5 Root surface area density in Caragana korshinskii forest land

2.2.3 Vertical Distribution of Root Length Density Root length density varied significantly with depth ($P < 0.05$), with intra-band values significantly higher than inter-band. Root length density ranged from 0.05–5.09 $cm \cdot cm^{-3}$

(intra-band) and 0.14–4.00 cm · cm^{-3} (inter-band). The 0–80 cm layer showed maximum values, representing 58.45% (intra-band) and 59.54% (inter-band) of total root length density. The 80–200 cm layer accounted for 16.37% and 16.07%, 200–440 cm for 13.52% and 11.01%, and 440–840 cm for 10.57% and 6.90%. Below 840 cm, root length density was minimal (6.98% and 1.20%). The concentration of roots in surface layers explains the greater water depletion and lower moisture content in these zones.

[Figure 6: see original paper]

Figure 6 Root length density in Caragana korshinskii forest land

2.3 Correlation Analysis

Correlation analysis between soil depth, root parameters, and water parameters revealed that soil depth was extremely significantly negatively correlated with root parameters ($P < 0.01$), indicating decreasing root density with depth. No significant relationship existed between soil depth and water parameters. Root parameters were extremely significantly correlated with each other ($P < 0.01$). Root surface area density and root dry weight were extremely significantly correlated with moisture content, desiccation degree, and water availability ($P < 0.01$). Root length density and root surface area density showed no significant correlation with water supply coefficient, while root dry weight was significantly correlated ($P < 0.01$).

Table 6 Correlation analysis of root parameters and water parameters

Parameter	Root Surface Area Density	Desiccation Degree	Water Availability
Root Surface Area Density	1	-0.87**	0.89**
Desiccation Degree	-0.87**	1	-0.96**
Water Availability	0.89**	-0.96**	1

Note: , ** indicate significant correlation at $P < 0.05$ and $P < 0.01$ levels, respectively.*

3 Discussion

Decades of artificial forest and grassland construction have increased vegetation coverage in the semi-arid Loess Plateau, but excessive water consumption has disrupted the dynamic balance between natural rainfall and native vegetation, causing soil desiccation. Previous studies reported desiccation layers reaching 22.4 m depth in the Loess Plateau [**?**], but the desiccation depth in southern Ningxia's belted C. korshinskii forests remained unclear. Our study found roots at 1000 cm depth, suggesting the desiccation layer may extend deeper, requiring further investigation.

Feng et al. [?] demonstrated that rainfall can infiltrate deep soil layers in semi-arid loess regions. We observed high moisture variability in the 0–300 cm layer due to current-year precipitation, while the 300–1000 cm layer was relatively stable. The poor water availability and low supply coefficients in 300–1000 cm indicate limited plant-available water. In the unique geomorphology of the Loess Plateau, groundwater recharge is difficult, and precipitation may minimally replenish soil below 300 cm, severely impairing the soil reservoir function—a key factor in vegetation decline and restoration challenges.

Soil desiccation results from inadequate water compensation by plant root uptake, making the root-soil interaction critical. Desiccation depth corresponds to root depth. Higher root density intra-band consumes more water for growth, reducing soil moisture compared to inter-band positions. C. korshinskii is a deep-rooted species; studies in Suide County, Shaanxi, reported root water uptake depths of 22.4 m [?]. Our investigation in southern Ningxia found living roots at 900 cm, shallower than the desiccation layer depth. This may be because our profile method could not distinguish C. korshinskii roots from co-occurring species. Root density decreases with depth, potentially creating desiccation layers deeper than the root zone.

Aging C. korshinskii forests may progressively deplete deeper soil moisture, requiring further study. Deep root research remains challenging, particularly in deep loess soils where perennial plant roots significantly impact soil physics, nutrients, water, carbon sequestration, and microbial communities. Strengthening root system research in loess regions is essential for understanding ecosystem processes.

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4 Conclusions

1. **Deep soil desiccation** occurred throughout the 0–1000 cm profile in C. korshinskii forest, with moisture content decreasing then increasing with depth, reaching minimum values around 440 cm. Both intra-band and inter-band positions showed varying water deficit degrees.

2. **Water availability** was poor across 0–1000 cm, with inter-band availability superior to intra-band. The water supply coefficient was consistently higher inter-band than intra-band, with both positions showing negative values below 440 cm, indicating limited plant-available water.

3. **Root distribution** was concentrated in the 0–80 cm layer, where root dry weight accounted for 45.56–46.33% of total, root length density for 58.45–59.54%, and root surface area density for 63.51–66.58%. Living roots extended to approximately 900 cm, shallower than the desiccation layer depth.

4. **Correlations** revealed that soil depth was extremely significantly negatively correlated with root parameters, while root parameters were ex-

tremely significantly correlated with moisture content, desiccation degree, and water availability. This confirms that intensive root distribution in surface layers drives soil moisture depletion and desiccation development.

These findings provide scientific guidance for sustainable vegetation management and water resource utilization in semi-arid loess regions.

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