

Postprint: Fine Root Response of Edible-leaf Forage in Saline-alkali Soil to Drought Rewatering

Authors: Zheng Xu

Date: 2022-01-26T00:00:00+00:00

Abstract

Rational formulation of irrigation cycles for halophytes is a key factor in improving water resource use efficiency in arid regions. Taking fine roots (d \leq 1 mm) of *Rumex crispus* as the research object, and using the drought-rewatering method, this study measured total root length, root tip number, and average root diameter of *Rumex crispus* fine roots at different times after rewatering, and investigated the variation characteristics of root growth rate, mortality, root lifespan, and turnover rate, to provide a reference basis for formulating optimal irrigation cycles. The results showed that root length and root tip number exhibited the greatest increase magnitude at 7 days after rewatering, with the growth magnitude weakening at 10-15 days. Fine root relative growth rate (RER) reached its maximum on day 4 after rewatering, and showed a significant decrease on day 10 ($P < 0.05$), with extremely significant differences observed among different soil layers (0-20 cm and 20-40 cm) and root diameters (0-0.5 mm and 0.5-1.0 mm) ($P < 0.001$). Both fine root net production (NRP) and RER exhibited a pattern of initial increase followed by decrease. At 15 days after rewatering, the survival rates of fine roots in the 0-20 cm and 20-40 cm soil layers were 3.6% and 16.9%, respectively, and the survival rate of fine roots with 0.5-1.0 mm diameter was higher than that of 0-0.5 mm fine roots. The study indicated that the median lifespan of fine roots after rewatering ranged from 8.09 to 13.83 days, with fine root lifespan in the 20-40 cm soil layer being significantly higher than that in the 0-20 cm layer ($P < 0.05$). *Rumex crispus* fine roots cope with and adapt to drought and rewatering by increasing 0.5-1.0 mm fine roots in the 20-40 cm soil layer, thereby achieving survival. Taking into comprehensive consideration the growth of *Rumex crispus* and agricultural water resource supply, the optimal irrigation cycle for *Rumex crispus* in saline-alkali soils during summer is 10 days.

Full Text

Response of *Rumex hanus* Fine Roots to Drought and Rehydration in Saline-Alkali Soil

ZHENG Xu, YANG Zhixin, HAO Dongmei, WANG Runrun, LI Luhua, ZHANG Fenghua, WANG Jiaping

(Agricultural College of Shihezi University, Shihezi 832000, Xinjiang, China)

Abstract

Rational formulation of irrigation cycles for halophytes is a key factor for improving water resource utilization efficiency in arid regions. This study examined the fine roots (diameter ≥ 1 mm) of *Rumex hanus* under drought and rehydration conditions to investigate changes in total root length, root tip number, average root diameter, root growth rate, mortality, root lifespan, and turnover rate at different times after rehydration, providing a reference basis for establishing optimal irrigation cycles. The results showed that root length and root tip number exhibited the greatest increase at 7 days after rehydration, with growth rates declining thereafter. The fine root elongation rate (RER) reached its maximum on day 4 after rehydration and decreased significantly by day 10 ($P < 0.001$). Significant differences were observed among different soil layers (0–20 cm and 20–40 cm) and root diameters (0–0.5 mm and 0.5–1.0 mm) ($P < 0.001$). Both net root production (NRP) and RER showed a pattern of initial increase followed by decrease. At 15 days after rehydration, the fine root mortality rates in the 0–20 cm and 20–40 cm soil layers were 3.6% and 16.9%, respectively. The survival rate of 0.5–1.0 mm diameter fine roots was higher than that of 0–0.5 mm fine roots. The lifespan of fine roots in the 20–40 cm soil layer (8.09–13.83 days) was significantly higher than in the 0–20 cm layer ($P < 0.05$). The results indicate that *Rumex hanus* fine roots respond to and adapt to drought and rehydration by increasing 0.5–1.0 mm fine roots in the 20–40 cm soil layer to achieve survival. Considering both plant growth and agricultural water resource availability, the optimal irrigation cycle for *Rumex hanus* in saline-alkali soils during summer is 10 days.

Keywords: saline-alkali soil; fine root; daily growth rate; mortality; turnover rate; median lifespan

Introduction

Water is a crucial factor affecting crop growth and development, and insufficient water supply during crop growth leads to drought stress, causing irreversible negative effects such as growth inhibition, premature senescence, and wilting. Arid regions frequently experience seasonal and intermittent drought, with increasing frequency in recent years. Roots are the primary organs for plants to absorb soil water and nutrients, and they respond first to drought stress. Root system research is key to revealing plant adaptation to drought environments.

However, due to the difficulty of root investigation, current understanding of root growth under drought stress and recovery mechanisms after rehydration remains limited.

Drought and rehydration occur sequentially in nature, and plant root growth and development show significant differences during this process. Studies have shown that *Seriphidium transiliense* exhibits increased root vitality and osmotic adjustment substances after drought rehydration, with reduced antioxidant enzyme activity, demonstrating stronger drought resistance. Drought and rehydration promote total root length, root volume, and average root diameter in oats. Research on tree seedlings indicates that fine root length, root diameter, and root dry weight increase after drought rehydration, with enhanced branching intensity improving seedling survival rates. However, most studies on roots under drought and rehydration have focused on total root systems, with insufficient attention to fine roots with diameters less than 1 mm. Therefore, investigating morphological changes, turnover, and lifespan of fine roots under drought stress and rehydration can provide practical basis for drought adaptation of halophytes and irrigation cycle formulation.

Rumex hanus is a high-yield, high-quality forage crop with saline-alkali tolerance, drought resistance, and cold tolerance, making it suitable for saline-alkali land improvement. Previous research on *Rumex hanus* has primarily focused on safety evaluation and its utilization in food, forage, and desertification land improvement. However, studies on root growth dynamics and rational irrigation in arid region saline-alkali soils have not been conducted. This study used one-year-old *Rumex hanus* as the research object to elucidate the response of fine root growth, mortality, and turnover to rehydration after drought in arid region saline-alkali soils and to formulate rational irrigation cycles. The results provide practical basis for root turnover of salt-tolerant plants and saline-alkali land restoration in arid regions.

1. Materials and Methods

1.1 Study Site The experiment was conducted at the Fifth Farm, General Farm, Shihezi City, Xinjiang (44°36' 1.75" N, 85°57' 35.72" E) from May to August 2020. The average daytime temperature during the experimental period was 32.5°C, and the nighttime average was 17.1°C. The experimental soil was gray desert soil with salt content of 0.4%–0.75%, pH 8.3–8.7, total nitrogen 0.28 g · kg⁻¹, and total phosphorus 0.75 g · kg⁻¹, classifying it as saline-alkali soil. *Rumex hanus* was planted on May 10, 2020, with row spacing of 60 cm. Drought treatment was initiated on July 20, 2020. The experiment used a randomized block design with three replicates, each plot measuring 3.6 m × 10 m = 36 m², with protective rows between plots.

1.2 Experimental Design Before rehydration, the CI-600 root monitoring system was used to scan the root systems of experimental plants to verify the detection area for roots with diameter <1 mm. Drought treatment lasted 15

days, after which rehydration was performed once with 150 m³ of water per hectare.

1.3 Micro-Rhizotron Installation The study employed micro-rhizotron technology to monitor *Rumex hanus* root growth. In June, during the seedling stage, a root monitoring system was installed using transparent plastic tubes (64 mm inner diameter, 1 m length) sealed at the bottom. The double-tube method was used, with tubes placed on both sides of the plant at a 45° angle to the ground. The sealed end was inserted into the soil, with the tube protruding approximately 10 cm above ground and positioned 10 cm from the plant. During measurement, black plastic caps were placed on the tubes to prevent debris entry, and black tape was wrapped around the outer wall to block light transmission.

1.4 Measurement Methods Root systems were monitored at 0, 4, 7, 10, and 15 days after rehydration. The scanning head was lowered using a pull rod, with rods installed every 20 cm on the rod connected to the scanning head. Images were obtained at depths of 0-20 cm and 20-40 cm. Each image measured 21.60 cm × 15.60 cm with a resolution of 1200 dpi and was saved in JPG format. Images were analyzed using WINRHIZOTRON 2015a software.

The latest image was superimposed on the previous image to track root evolution and report new characteristics and status: roots that remained milky white and had elongated were classified as live roots, while roots that were dead or showed obvious signs of decay (shriveled, transparent, faint, or blackened) were classified as dead roots. To verify root death status, continuous images recorded at the same root tube position were analyzed to ensure dead roots remained black without growth. Root diameter, live and dead root lengths, and shapes of new roots were recorded for all images.

1.5 Calculation of Root Characteristic Indices **Live Length Production (LLP)** and **Dead Length Loss (DLL)** represent the total length of live or dead roots from time t to $t+\Delta t$ (where Δt is the root scanning interval):

$$LLP (DLL) = \sum(l) / A$$

where l is the length of live (or dead) root i (cm), n is the number of roots, A is the soil area observed in the scanning image (m²), and Δt is the scanning interval (days).

Cumulative Live Length Production (CLLP) and **Cumulative Dead Length Loss (CDLL)** represent the total length of live or dead roots up to time t :

$$CLLP (CDLL) = \sum LLP (DLL)$$

Net Root Production (NRP) is the cumulative live root length minus cumulative dead root length within time t :

$$\text{NRP} = \text{CLLP} - \text{CDLL}$$

Cumulative Net Root Production (CNRP) is the cumulative total length of live roots within time t :

$$\text{CNRP} = \sum \text{NRP}$$

Dead Root Number (DN) calculates the difference in dead roots between t and $t+\Delta t$:

$$\text{DN} = (N_{\{\text{dead}\}} \Delta - N_{\{\text{dead}\}}) / A$$

where $N_{\{\text{dead}\}}$ is the number of dead roots, A is the soil area (m^2), and Δt is the time interval between measurements.

Root Elongation Rate (RER) is calculated by determining individual root growth from the difference in root length between times t and $t+\Delta t$:

$$\text{RER} = (1/N) \sum (l \Delta - l) / \Delta t$$

where n is the root growth rate ($\text{cm} \cdot \text{d}^{-1}$), N is the total number of live or dead roots, and Δt is the time interval between samplings (days).

All variables correspond to root diameters (0-0.5 mm, 0.5-1.0 mm) and soil depths (0-20 cm, 20-40 cm).

Root Survival Rate (S) and **Median Lifespan** were determined using non-parametric Kaplan-Meier methods. Each fine root growing within a given time period was considered independent and classified as surviving or dead at the study conclusion. Root lifespan was calculated as the number of days from first observation to death. Median lifespan (ML) is the median time from root emergence to death, and turnover rate (T) is the reciprocal of median lifespan:

$$T = 1/\text{ML}$$

1.6 Statistical Analysis Using root elongation rate, net root production, and cumulative dead root length as dependent variables, and root diameter and soil depth as independent variables, a generalized linear model (GLM) was employed. Considering interactions between factors, one-way ANOVA was used for significance testing ($P < 0.05$). SPSS 21.0 software was used for data processing, statistical analysis, and non-parametric Kaplan-Meier survival analysis. Origin 8.5 software was used for graphing.

2. Results and Analysis

2.1 Changes in Root Length, Average Root Diameter, and Root Tip Number Before and After Rehydration The total length and tip number of *Rumex hancus* fine roots in both soil layers increased significantly after rehydration (Table 1), while average root diameter showed the opposite trend. Total root length increased from 1097.9 cm to 1448.7 cm (a 24.2% increase), and root tip number increased from 307.1 to 497.9 (a 62.1% increase). The increase

in total root length in the 20–40 cm layer was slightly higher than in the 0–20 cm layer, but the difference was not significant ($P = 0.21$). Root tip changes showed a similar trend ($P = 0.08$). Average root diameter decreased from 0.74 mm to 0.63 mm ($P = 0.12$).

During 0–4 days after rehydration, few new roots were produced, with existing roots being dominant. During 4–7 days after rehydration, root length and tip number in both soil layers showed the largest increases. The increase amplitude in the 20–40 cm layer was greater than in the 0–20 cm layer, but the difference was not significant ($P = 0.21$ for root length, $P = 0.08$ for root tips). During 7–15 days after rehydration, the proportion of new roots decreased while existing roots remained dominant, and the growth rate gradually declined.

For 0.5–1.0 mm diameter roots in the 0–20 cm and 20–40 cm layers, root length increases reached 13.0% and 17.8%, respectively, while root tip number increases reached 14.9% and 13.4%, respectively. During 4–7 days after rehydration, root length increases reached 14.6% and 23.6%, respectively, while root tip number increases reached 32.6% and 18.6%, respectively. Average root diameter decreased from 0.65 mm to 0.50 mm.

Table 1 Variation characteristics of fine root length (0–1.0 mm), root tip number, and average root diameter of *Rumex hanseni* at different depths after rehydration

Days after rehydration	Root length (cm)	Root tip number	Average root diameter (mm)
	0–20 cm	20–40 cm	0–40 cm
0	473.3 \pm 62.6b	624.6 \pm 46.8a	1097.9 \pm 86.3
	162.3 \pm 32.2a	144.8 \pm 33.8a	307.1 \pm 56.2
	0.86 \pm 0.22		

Note: Different lowercase letters indicate significant differences between soil layers at $P < 0.05$.

2.2 Changes in Root Diameter Growth Rate at Different Depths After Rehydration Soil depth had a highly significant effect on *Rumex hanseni* root length growth rate ($P < 0.001$). The overall trend of root length growth rate showed an initial increase followed by a decrease. The 20–40 cm soil layer exhibited significantly higher root growth rates than the 0–20 cm layer, with more pronounced fluctuations. During 0–7 days after rehydration, root growth rates in both layers increased, reaching maximum values on day 7. During 7–15 days, root growth rates in both layers decreased, with growth trends converging, indicating the disappearance of rehydration compensation effects.

Root diameter ($P < 0.001$) and soil depth ($P < 0.001$) had highly significant effects on fine root growth rate. Fine roots of 0–0.5 mm diameter showed an initial increase followed by decrease, with the highest growth rate of 0.647 $\text{cm} \cdot \text{d}^{-1}$ occurring at 4 days after rehydration in the 0–20 cm layer, after which

growth rates gradually declined. In the 20–40 cm layer, the maximum growth rate of $0.463 \text{ cm} \cdot \text{d}^{-1}$ occurred at 7 days after rehydration. The compensation effect of 0.5–1.0 mm fine roots decreased after 7 days.

The maximum growth rates of 0–0.5 mm fine roots differed between soil layers, occurring at 4 days in the 0–20 cm layer and 7 days in the 20–40 cm layer. For 0.5–1.0 mm fine roots, the maximum growth rate in the 0–20 cm layer was $0.664 \text{ cm} \cdot \text{d}^{-1}$ at 4 days, while in the 20–40 cm layer it was $0.881 \text{ cm} \cdot \text{d}^{-1}$ at 7 days.

Table 2 ANOVA model for root elongation rate (RER), cumulative net root production (CNRP), and cumulative dead length loss (CDLL) as functions of fine root diameter, soil depth, and interactions between factors

Factor	RER	CNRP	CDLL
Root diameter	<0.001	<0.05	<0.01
Soil depth	<0.001	<0.001	<0.001
Diameter \times Depth	0.21	0.08	0.12

Figure 1 [Figure 1: see original paper] Characteristics of daily growth rate of fine roots at different depths after rehydration

2.3 Net Production and Mortality of Fine Roots After Rehydration

Soil depth significantly affected the cumulative dead root length of *Rumex hanus* fine roots ($P < 0.001$), and root diameter had a significant effect ($P < 0.05$). Soil depth also significantly affected fine root survival rate ($P = 0.032$). After rehydration, root survival rates exceeded 93.9%, but began to decline significantly after 4–7 days, reaching 70.6% by day 15.

With increasing time after rehydration, different patterns emerged. Fine roots in the 20–40 cm layer began dying in large numbers after 7 days, while those in the 0–20 cm layer began massive death after 10 days, indicating a lag in deep fine root mortality. Fine root mortality was concentrated in the 0–0.5 mm diameter class, accounting for 62.4% of dead root length and 58.2% of dead root numbers. Net root production (NRP) and cumulative dead root length showed an initial increase followed by decrease.

At 15 days after rehydration, fine root mortality in the 0–20 cm and 20–40 cm layers was 3.6% and 16.9%, respectively ($P < 0.05$). The survival rate of 0.5–1.0 mm diameter fine roots was higher than that of 0–0.5 mm fine roots ($P < 0.05$). Fine root net production peaked at 7 days after rehydration, with maximum dead root amounts of $6.22 \text{ cm} \cdot \text{m}^{-2}$ in the 0–20 cm layer and $3.51 \text{ cm} \cdot \text{m}^{-2}$ in the 20–40 cm layer.

Figure 2 [Figure 2: see original paper] Net production of fine roots (a) and accumulation of dead roots in different soil layers (b) after rehydration

Table 3 Cumulative live root length production (CLLP) and cumulative dead length loss (CDLL) in 0–40 cm soil layer

Root diameter (mm)	CLLP (cm · m ⁻²)	CDLL (cm · m ⁻²)	Proportion of total root length (%)	RER (cm · d ⁻¹)
0–0.5	112.3a	106.8a	62.4a	0.31\$±0.22a 0.5–1.0 24.4b 62.7a 37.3b 0.

Note: Different letters indicate significant differences at $P < 0.05$.

2.4 Effects of Root Diameter and Soil Depth on Fine Root Turnover Rate After Rehydration

Root diameter and soil depth significantly affected *Rumex hanus* fine root lifespan ($P < 0.05$). Root diameter significantly affected cumulative dead root length (CDLL) ($P < 0.05$). Fine root turnover rates ranged from 1.08 to 1.85 per cycle, decreasing with increasing diameter. Median lifespans were 9.90–13.83 days. In the 0–20 cm layer, median lifespans for 0–0.5 mm and 0.5–1.0 mm fine roots were 9.90 days and 11.35 days, respectively ($P < 0.05$). In the 20–40 cm layer, median lifespans were 11.41 days and 13.83 days, respectively, with significant differences between layers ($P < 0.05$).

Figure 3 [Figure 3: see original paper] Survival rate of roots of *Rumex hanus* in different soil layers after rehydration (a) and the root survival rate of different diameters (b)

Table 4 Median lifetime of root system with different soil layers and diameters

Soil depth (cm)	0–0.5 mm	0.5–1.0 mm
0–20	9.90\$±0.27b 11.35±0.28a 20–40 11.41±0.35b 13.83±\$0.33a	

Table 5 Median lifetime of roots with different diameters under 0–40 cm soil layers

Root diameter (mm)	Median lifespan (days)
0–0.5	8.09\$±0.33c 0.5–1.0 10.62±0.50b 20–40(0–0.5) 11.62±0.39a 20–40(0.5–

3. Discussion

3.1 Effects of Rehydration on Fine Root Morphology in Saline-Alkali Soil

Fine roots are the primary organs for water and nutrient absorption. Dynamic changes in root length, root volume, and average root diameter reflect plant responses to drought stress and are important indicators for evaluating drought resistance. Drought and rehydration produce compensatory effects on plants, with roots being the first to respond. This study found that after drought

rehydration, root length and root tip number initially increased then decreased, with maximum root length increase (40.7 cm) occurring at 7 days after rehydration. This is consistent with research on oats by Wang Xiaoxue et al., as rehydration promotes the production of more absorptive roots, demonstrating that rehydration can restore plant root growth.

After rehydration, the average root diameter of *Rumex hanus* decreased due to increased root length and tip number, which reduced the average diameter and promoted root growth. This aligns with the conclusion of Wei Qingjiang et al. on reduced root diameter in citrus under drought rehydration. Hao Shurong et al. found that drought stress followed by rehydration during rice tillering increased root length and tip number, indicating compensatory effects, which is consistent with our results on *Rumex hanus*.

3.2 Effects of Root Diameter and Soil Depth on Fine Root Growth

Rate Root growth rate is an indicator of root activity, with higher rates indicating more suitable growing conditions. Studies show that fine root growth rates decrease with increasing soil depth. This study found that the 0-20 cm soil layer had higher growth rates than the 20-40 cm layer, which differs from research on Korean pine by Wang Cunguo et al. This discrepancy may be due to our use of one-year-old *Rumex hanus* plants where the root growth center had shifted from the 0-20 cm to the 20-40 cm layer, with new fine roots appearing in the 0-20 cm layer at 4 days after rehydration and in the 40 cm layer at 7 days. The study by Wang Cunguo et al. used pine seedlings whose root growth centers were still in shallow soil layers.

Fine root distribution in deep soil significantly affects water and nutrient absorption. Most fine roots (primarily 0-1.0 mm) are distributed in surface soil, but deep roots show greater fluctuations during drought periods. This study found that fluctuations in the 20-40 cm layer were significantly greater than in the 0-20 cm layer, consistent with research on *Schima superba* by Zhang Kun et al., suggesting that perennial plants may respond to soil moisture changes through variations in deep fine root growth.

Both root diameter and soil depth affect fine root growth rate and accumulation. This study showed that 0-1.0 mm fine roots were primarily distributed in the 0-20 cm layer, accounting for approximately 58% of monitored roots. Root diameter and soil depth significantly affected root length, consistent with previous research. However, the interaction between root diameter and soil depth did not significantly affect fine root growth rate, similar to results from studies on hybrid walnut (*Juglans regia* × *nigra*) by Germon et al., indicating that soil first promotes root length increase, then root diameter increase, suggesting soil has some inhibitory effect on diameter increase.

3.3 Effects of Soil Depth on Fine Root Mortality

Fine root mortality decreases with increasing root diameter. Plants retain thicker (1-2 mm) fine roots because they play important roles in resource transport and fixation and

are producers of new roots. Different diameter fine roots have varying mortality rates. Coarse roots have higher carbohydrate content, primarily lignin and cellulose, and lower nutrient content. Higher soil moisture promotes fine root growth and improves root survival capacity. In terms of growth cost, fine roots have lower construction costs. Under special conditions (drought, salinity), plants increase investment in coarse roots to maintain basic survival.

This study found that 0–0.5 mm fine root mortality was significantly higher than 0.5–1.0 mm fine roots after 5–15 days of rehydration ($P < 0.05$), consistent with research by Zhou Yongjiao et al. The reason may be that low aboveground biomass during early drought provided insufficient photosynthates to meet the energy demands of these fine roots, and long-distance transport consumed additional energy. Root mortality in the 0–20 cm layer was significantly higher than in the 20–40 cm layer ($P < 0.05$), possibly because surface roots were more affected by soil evaporation, tillage practices, and soil temperature, leading to root death, similar to findings on marsh herbs by Yang Weizong et al.

3.4 Effects of Rehydration on Fine Root Turnover Rate The fine root turnover rate of *Rumex hanus* ranged from 1.08 to 1.85 per cycle, slightly higher than the 0.63–1.25 per cycle reported for oats after drought rehydration. This difference may be due to oats being annual plants while *Rumex hanus* is perennial, with different root growth patterns leading to varying turnover rates. Research shows that irrigation frequency significantly affects processing tomato roots, with optimal root biomass, distribution, and water use efficiency achieved at 10-day irrigation intervals. Studies on oats and greenhouse cucumbers indicate that 8–10 day irrigation intervals promote deep root distribution, increase total root biomass, and improve yield.

This study found that *Rumex hanus* root growth slowed and fine roots began obvious death 10 days after rehydration in saline-alkali soil. Considering rational saline-alkali land development and water resource conservation, an irrigation cycle of 8–10 days meets *Rumex hanus* growth requirements while alleviating water scarcity.

4. Conclusion

By investigating the growth, development, and senescence processes of *Rumex hanus* fine roots after drought rehydration in saline-alkali soil, along with dynamic changes in root survival rates, this study found that fine root survival rates remained at 93.9% within 4 days after rehydration, then declined significantly to 70.6% by day 15. Root length and tip numbers in the 0–40 cm layer increased by 24.2% and 62.1% compared to pre-rehydration levels, indicating that *Rumex hanus* restores growth by expanding its water absorption range after drought rehydration.

The net production and mortality of fine roots in the 0–40 cm layer showed increases of 14.8% and 35.4%, respectively, partially offsetting each other. The

20–40 cm layer exhibited higher turnover rates, survival rates, and median lifespans than the 0–20 cm layer. The 0.5–1.0 mm diameter roots demonstrated stronger adaptability than 0–0.5 mm roots, with higher growth rates and median lifespans. Root growth, survival rates, and accumulation of *Rumex hanus* all decreased significantly after 10 days, with large-scale death of 0–0.5 mm fine roots, indicating that fine roots can maintain growth for 8–10 days. The dynamic response of *Rumex hanus* fine roots to rehydration reflects its adaptive strategy to the environment and provides a theoretical basis for irrigation management of halophytes in arid regions.

References

- [1] Zhao B, Ma B L, Hu Y, et al. Source sink adjustment: A mechanistic understanding of the timing and severity of drought stress on photosynthesis and grain yields of two contrasting oat (*Avena sativa*) genotypes[J]. *Journal of Plant Growth Regulation*, 2021, 40(5): 263-276.
- [2] Malota M, Mchenga J. Matching soil salinization and cropping systems in communally managed irrigation schemes[J]. *Applied Water Science*, 2018, 8(1): 14-16.
- [3] Gong Zitong, Chen Hongzhao, Yang Fan, et al. Pedogeochemistry and environment of aridisol regions in Central Asia[J]. *Arid Zone Research*, 2017, 34(1): 1-9.
- [4] Li Guanghui, Wan Yongshan, Liu Fengzhen, et al. Morphological and physiological traits of root in different drought resistant peanut cultivars[J]. *Acta Agronomica Sinica*, 2014, 40(3): 531-541.
- [5] Wang Xiaoxue, Li Yue, Zhang Bin, et al. Effects of drought stress and rehydration on root growth and physiological characteristics of oats[J]. *Acta Agrestia Sinica*, 2020, 28(6): 103-111.
- [6] Chen Aiping, Sui Xiaoqing, Wang Yuxiang, et al. Effects of drought and rewatering on growth and physiological characteristics of *Seriphidium transiliense* seedlings[J]. *Acta Agrestia Sinica*, 2020, 28(5): 48-57.
- [7] Wang Cunguo, Brunner Ivano, Guo Wei, et al. Effects of long term water reduction and nitrogen addition on fine roots and fungal hyphae in a mixed mature *Pinus koraiensis* forest[J]. *Plant and Soil*, 2021, 16(4): 1-13.
- [8] Daoqian C, Shiwen W, Beibei C, et al. Genotypic variation in growth and physiological response to drought stress and rewatering reveals the critical role of recovery in drought adaptation in maize seedlings[J]. *Frontiers in Plant Science*, 2015, 6(6): 124-133.
- [9] Germon A, Cardinael R, Prieto I, et al. Unexpected phenology and lifespan of shallow and deep fine roots of walnut trees grown in a silvoarable Mediterranean agroforestry system[J]. *Plant and Soil*, 2016, 401(1): 409-426.

- [10] Pregitzer K S, King J S, Burton A J, et al. Responses of tree fine roots to temperature[J]. *New Phytologist*, 2010, 147(1): 105-115.
- [11] Pregitzer K S, Deforest J L, Burton A J, et al. Fine root architecture of nine north American trees[J]. *Ecological Monographs*, 2002, 72(2): 293-309.
- [12] McCormack M, Dickie I, Eissenstat D, et al. Redefining fine roots improves understanding of below ground contributions to terrestrial biosphere processes[J]. *New Phytologist*, 2015, 207(3): 505-518.
- [13] Zadworny M, Eissenstat D M. Contrasting the morphology, anatomy and fungal colonization of new pioneer and fibrous roots[J]. *New Phytologist*, 2011, 190(1): 213-221.
- [14] Liu Y, Wang G, Yu K, et al. A new method to optimize root order classification based on the diameter interval of fine root[J]. *Scientific Reports*, 2018, 8(1): 2960-2978.
- [15] Li M, Wang Y, Adeli A, et al. Effects of application methods and urea rates on ammonia volatilization, yields and fine root biomass of alfalfa[J]. *Field Crops Research*, 2018, 218(8): 115-125.
- [16] Zhang Meng, Liu Ning, Wang Xuejian, et al. Effects of reduced precipitation and herb competition on the morphological and physiological characteristics of the fine roots of *Betula platyphylla* seedlings[J]. *Journal of Northwest Forestry University*, 2021, 36(4): 73-79.
- [17] Lou Minhan, Qu Xuefeng, Zhang Lijing, et al. Safety evaluation of edible dock as a new food raw material[J]. *Journal of Food Safety & Quality*, 2021, 12(10): 3919-3926.
- [18] Zhou Xin, Huang Qiulian, Wang Jian, et al. Effects of adding lactic acid bacteria and molasses on fermentation quality and in vitro dry matter disappearance rate of *Rumex hanus* silage with different moisture contents[J]. *Chinese Journal of Animal Nutrition*, 2021, 33(3): 1594-1606.
- [19] Zhang C M, Shi S L, Wang B W, et al. Physiological and biochemical changes in different drought tolerant alfalfa (*Medicago sativa* L.) varieties under PEG induced drought stress[J]. *Acta Physiologiae Plantarum*, 2018, 40(2): 25-40.
- [20] Wang W J, He H S, Zu Y G, et al. Addition of HPMA affects seed germination, plant growth and properties of heavy saline alkali soil in northeastern China: Comparison with other agents and determination of the mechanism[J]. *Plant and Soil*, 2011, 339(1): 177-191.
- [21] Wei Jiangqing, Feng Fangfang, Ma Zhangzheng, et al. Effects of drought and rewatering on leaf photosynthesis, chlorophyll fluorescence, and root architecture of citrus seedlings[J]. *Chinese Journal of Applied Ecology*, 2018, 29(8): 2485-2492.

- [22] Hao Shurong, Guo Xiangping, Wang Weimu, et al. Effects of water stress in tillering stage and re watering on rice root growth[J]. *Agricultural Research in the Arid Areas*, 2007, 25(1): 149-152.
- [23] Chen W L, Jin M G, Ferre T P A, et al. Spatial distribution of soil moisture, soil salinity, and root density beneath a cotton field under mulched drip irrigation with brackish and fresh water[J]. *Field Crops Research*, 2018, 215(7): 207-221.
- [24] Zheng J, Fan J L, Zhang F C, et al. Evapotranspiration partitioning and water productivity of rainfed maize under contrasting mulching conditions in Northwest China[J]. *Agricultural Water Management*, 2021, 243(3): 473-488.
- [25] Mao Z, Bonis M L, Rey H, et al. Which processes drive fine root elongation in a natural mountain forest ecosystem?[J]. *Plant Ecology & Diversity*, 2013, 6(2): 231-243.
- [26] Beyer F, Hertel D, Jung K, et al. Competition effects on fine root survival of *Fagus sylvatica* and *Fraxinus excelsior*[J]. *Forest Ecology & Management*, 2013, 302(2): 14-22.
- [27] Zheng J, Fan J L, Zhang F C, et al. Evapotranspiration partitioning and water productivity of rainfed maize under contrasting mulching conditions in Northwest China[J]. *Agricultural Water Management*, 2021, 243(3): 473-488.
- [28] Costa C, Filho A, Crusciol C, et al. Intensive annual crop production and root development in a tropical acid soil under long term no till and soil amendment management[J]. *Crop & Pasture Science*, 2018, 69(5): 488-506.
- [29] Tian Xiaoxia, Mao Peichun, Guo Qiang, et al. Effect of cadmium on root morphology and partial physiological indexes of *Iris lacteal chinensis*[J]. *Acta Botanica Boreali Occidentalia Sinica*, 2019, 39(6): 1105-1113.
- [30] Zhou Yongjiao, Wang Mantang, Wang Zhaoying, et al. Nutrient and ecological stoichiometry of different root order fine roots of 59 evergreen and deciduous tree species in subtropical zone[J]. *Acta Ecologica Sinica*, 2020, 40(14): 4975-4984.
- [31] Keel S G, Campbell C D, Mn H, et al. Allocation of carbon to fine root compounds and their residence times in a boreal forest depend on root size class and season[J]. *New Phytologist*, 2012, 194(4): 972-981.
- [32] Çerçio lu M, Anderson S H, Udawatta R P, et al. Effect of cover crop management on soil hydraulic properties[J]. *Geoderma*, 2019, 343(3): 247-253.
- [33] Richter D deB, Billings S A. One physical system: Tansley review of Earth's critical zone[J]. *New Phytologist*, 2015, 206(1): 242-257.
- [34] Zhao Jianing, Liang Yun, Liu Ying, et al. Patterns and influence factors of fine root turnover in forest ecosystems[J]. *Bulletin of Botany*, 2020, 55(3): 308-317.

- [35] Prieto I, Roumet C, Cardinael R, et al. Root functional parameters along a land use gradient: Evidence of a community level economics spectrum[J]. *Journal of Ecology*, 2015, 103(2): 361-373.
- [36] Ni Huijing, Su Wenhui, Fan Shaohui, et al. Responses of forest soil nutrient cycling to nutrient input modes: A review[J]. *Chinese Journal of Ecology*, 2019, 38(3): 863-872.
- [37] Hu Qijuan, Sheng Maoyin, Yin Jie, et al. Stoichiometric characteristics of fine roots and rhizosphere soil of *Broussonetia papyrifera* adapted to the karst rocky desertification environment in southwest China[J]. *Chinese Journal of Plant Ecology*, 2020, 44(9): 962-972.
- [38] Wang Qun, Zhao Xiangyang, Liu Dongyao, et al. Root morphological, physiological traits and yield of maize under waterlogging and low light stress[J]. *Scientia Agricultura Sinica*, 2020, 53(17): 3479-3495.
- [39] Liao Yining, Guo Sujuan, Wang Fangfang, et al. Effects of combined application of organic and inorganic fertilizers on soil fertility and root functional traits in chestnut orchards[J]. *Journal of Nanjing Forestry University (Natural Sciences Edition)*, 2021, 45(5): 84-92.
- [40] Blanco C H, Shaprio C, Jasa P, et al. No till and carbon stocks: Is deep soil sampling necessary? Insights from long term experiments[J]. *Soil and Tillage Research*, 2021, 206(6): 883-893.
- [41] Zhang Kun, Diao Ming, Jing Bo, et al. Influence of irrigation quota and frequency on root growth and yield of processing tomato[J]. *Journal of Drainage and Irrigation Machinery Engineering*, 2020, 38(1): 83-89.
- [42] Yang Dongyan, Feng Haiping, Zhao Yunxia, et al. Effects of irrigation frequency on yield and root distribution characteristics of greenhouse autumn winter planted cucumber[J]. *Water Saving Irrigation*, 2020, 298(6): 25-28.
- [43] Wu Yibo, Che Rongxiao, Ma Shuang, et al. Estimation of root production and turnover in an alpine meadow: Comparison of three measurement methods[J]. *Acta Ecologica Sinica*, 2014, 34(13): 3529-3537.
- [44] Yang Weizong, Ma Xiao, Yang Wen, et al. Seasonal dynamics of biomass, root turnover, and carbon, nitrogen and phosphorus storage of Zoige alpine marsh[J]. *Chinese Journal of Ecology*, 2021, 40(5): 1285-1292.
- [45] Zhao Liping, Liu Jiayong, Zhao Peifang, et al. The impact of water stress on the growth of roots and above ground parts in sugarcane[J]. *Journal of Hunan Agricultural University (Natural Sciences)*, 2019, 45(1): 10-15.

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

Source: ChinaXiv – Machine translation. Verify with original.