Response of Fine Root Growth of Stumped *Hippophae Rhamnoides* to Environmental Changes in Feldspathic Sandstone Areas of Ordos

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Abstract: In this study targeted at 13a stumped *Hippophae rhamnoides* in feldspathic sandstone areas of Inner Mongolia, China, we studied how the root length density growing rate (RLD_{gr}) of stumped *H. rhamnoides* at decay stage responded to environmental changes in feldspathic sandstone areas. The RLD_{gr} of fine roots at soil depth of 0-100 cm in April to October was measured using the minirhizotron technique, and the seasonal characteristics of RLD_{gr} in the growing season were analyzed and summarized. The changing relationships of RLDgr to surrounding environmental factors (soil moisture content (%); soil temperature (℃); Ta (℃); relative humidity (H_R, %); vapor pressure deficit (D_{VP}, kPa); photosynthetically active radiation (R_{PA}, $W \cdot m^{-2}$)) were studied. Since the severe multicollinearity among factors during multiple linear regression makes regression models unstable, ridge regression was adopted to diagnose multicollinearity among environmental factors. After some unstable factors were removed, regression models between RLD_{gr} of stumped *H. rhamnoides* and environmental factors were established. (1) The seasonal variation in RLD_{gr} of *H. rhamnoides* shows a single peak in fall, and RLD_{gr} is the fastest in July and August. RLD_{gr} grows the fastest at the soil depth of 0-15 cm, and decreases with the decline of soil depth. (2) Soil moisture content, soil temperature, *Ta*, D_{VP}, and R_{PA} are all positively correlated with RLD_{gr}, but H_R is negatively correlated with RLD_{gr}. (3) The ridge regression equation between post-stumping RLD_{gr} and environmental factors is $y = 0.29 + 0.254X_1 + 0.253X_2 + 0.427X_3 - 0.104X_4$, where y is RLD_{gr}, $mm \cdot cm^{-3}$; X_1 is soil moisture content; X_2 is soil temperature; X_3 is Ta; X_4 is HR. Based on analytical results, soil moisture content, soil temperature, Ta, and HR were selected as explaining variables of RLD_{gr}, and the influence degree on post-stumping RLD_{gr} rank as Ta > soil temperature > soil moisture content > H_R. The relationship between post-stumping RLD_{gr} and environmental factors in feldspathic sandstone habitats was statistically analyzed. A stable regression model was finally obtained to clarify the environmental factors that largely affected post-stumping RLD_{gr} and the mechanism how stumped *H. rhamnoides* responded to the growing environment. This study offers a new clue for eco-construction in feldspathic sandstone areas and for accelerated administration of soil-water loss. Our findings are valuable for resource utilization in feldspathic sandstone areas.

Keywords: feldspathic sandstone; *hippophae rhamnoides*; fine root growing rate; environmental factors

1. Introduction

Feldspathic sandstone is a type of loose strata in which the degree of consolidation between sand grains is low. Normally, feldspathic sandstone is very firm and undestroyable, but will turn to mud upon the contact with water and turn to sand in case of winds. Hence, massive water and soil loss occurs easily in feldspathic sandstone areas, which carry off numerous nutrients in soils and lead to soil fertility decline and soil leanness, inducing land desertification and severe soil erosion. Feldspathic sandstone areas are called "cancer of the geo-environment" owing to the difficulty in administration and eco-environment restoration [1]. Feldspathic sandstone contains low organic contents and lacks necessary nutrients for crop growth. Thus, crop survival rate in feldspathic sandstone areas is low, and the growth and yield of crops are interfered to some extent.

During stumping, the branches above the collar of a seedling after 2 to 3 years of transplanting are all cut off at certain height, which will enhance the sprouting ability of the seedling and drive it to grow thick and strong branches [2,3]. *Hippophae rhamnoides* is a deciduous shrub with flourishing roots and is featured by fast growing rate, drought tolerance and strong adaptability. It is a pioneer tree species in feldspathic sandstone areas [4]. *H. rhamnoides* has well-developed lateral roots with strong sprouting ability, which can strongly occupy the underground space and consolidate soils and prevent soil-water loss. *H. rhamnoides* can improve soil moisture content, porosity, soil organic content, soil fertility and physiochemical properties [5].

Fine roots are the most active part of a root system and are vital organs of plants that can absorb moisture and nutrient and exchange minerals and organic matter with the environment, and release root-derived secretes [6]. The underground part of plants is the key organ that decides the survival and adaptability of plants and can reconstruct habitats, control soil-water loss, improve fertilizers and solidate soils [7]. Fine roots are defined as roots in diameter < 2 mm [8]. Fine roots possess large absorptive surface area, and the growth and development of plants depend on the derivation of nutrients from soils. The roots of both grasses and brushes can significantly solidate soils [9] by inserting and intertwining soils [10], which effectively alleviate surface soil loss. Moreover, roots can significantly improve structural stability and erosion resistance of soils, and prevent and control soil erosion [11]. Compared with grasslands, *H. rhamnoides* can better improve soils [12]. The dry branches and fallen leaves of *H. rhamnoides* form a humus layer that can improve organic content in soils and recover soil fertility, and the rhizobia can improve soils. Thus, research on fine roots of *H. rhamnoides* is extremely important.

In this study, the environmental factors of interest include climate factors and soil factors. As reported, the species diversity of a microscopic environment is affected by environmental factors, including temperature, illumination and moisture. Temperature directly affects plant diversity, and when illumination time is prolonged, temperature rises, which will promote the seed germination of constructive species. However, excessively high temperature will threaten plant growth and is unfavorable for plantal growth and development, thereby interferring plantal diversity [13]. The types of site conditions also affect the growing properties and nutrients of *H. rhamnoides* [14]. In arid and semiarid areas, moisture is among the major restricting factors during plant growth, and plays a very important and indispensable role in plant growth and development [15].

The study area is Nuanshui Village in Ordos, Inner Mongolia, China, which is a typical feldspathic sandstone area. Then the environmental effects on the growth characteristics of fine roots of *H. rhamnoides* were explored. The importance of *H. rhamnoides* in feldspathic sandstone areas has been extensively approved by researchers recently. However, no research has concerned both the growing characteristics of *H. rhamnoides* fine roots before or after stumping and environmental factors in feldspathic sandstone areas. This study can fill in some of the blank and provide reference and value for future research in this field.

1.1. The Study Area

The study area is located in Geqiu groove watershed (39°42′ - 39°50′ N, 110°25′ - 110°48′ E) of Nuanshui Village, Jungar Banner, Ordos, Inner Mongolia. (The basic information of the plots is listed in Figure 1.) This watershed has fluctuating terrains and numerous gullies, with fluctuating girders, but suffers intense soil erosion and severe soil-water loss. With an average altitude of 1044 m, this area enjoys a typical moderate temperature semiarid continental monsoon climate, with average sunshine duration of 3000 h and frost-free period of 148 d. The annual average precipitation is about 400 mm, which is concentrated in July and August. The annual evaporation is 2093 mm, annual average temperature is 6.2 - 8.7 ºC, accumulative temperature ≥10 ºC is 2900-3500 ℃, and yearly total radiation is 5.8 GJ/m^2·y. The soil type is dominated by loessial soil and accompanied by feldspathic sandstone landscapes, which are mainly chestnut soil and sand soil. This watershed is planted mainly with artificial vegetation for soil/water conservation, wind prevention and sand fixation. The major afforestation species include *H. rhamnoides*, *Pinus tableulaeformis*, *Caragana korshinskii*, *Medicago sativa*, and *Prunus sibirica*. The major vegetation under artificial *H. rhamnoides* forests includes *Leymus chinensis*, *Stipa krylovii*, and *Cleistogenes squarrosa*.

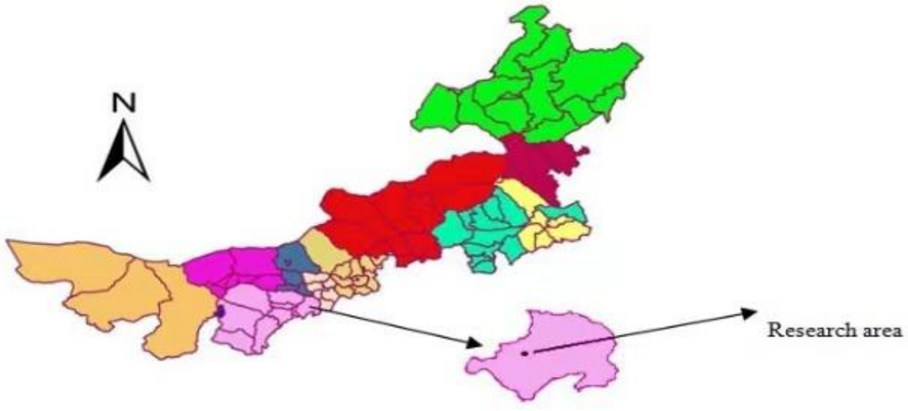

Figure 1. Location of the study area

1.2. Methods

1.2.1. Survey and sampling

A 13a stumped *H. rhamnoides* artificial forest land in the study was selected in 2018 as the experimental field. The stumped *H. rhamnoides* was chosen. Specifically, 3 plots of the stumped artificial forest land with basically consistent site conditions, management measures and growing conditions were selected. The 3 plots were all 50m×50m in area and at slope lower than 5°. In each plot, the tree distance × row distance was 2m×4m. To better study the relationships between fine roots of stumped *H. rhamnoides* and environmental factors of habitats, we selected the stubble height of 10 cm. In middle March 2018, the trees in all 3 plots were stumped. In the middle of every month from April to October in both 2018 and 2019, the trees were measured. Minirhizotrons were installed simultaneously with stumping. To avoid the marginal effect, we installed the minirhizotrons all in the center of each plot. Hence, 3 standard *H. rhamnoides* clusters (each with plant height 83 cm, NS canopy size 108 cm, EW canopy size 130 cm, average of 7 branches) were chosen from each stumped plot. The minirhizotrons were installed at 0 cm of trees. Totally 9 devices were installed in the 3 plots. Root-related information was collected at the depth of 1 m and within the radius of 2 m. The basic information of the plots is listed in Table 1.

Table 1. Statistics of *H. rhamnoides* sampling plots

Plot	Standard cluster	Soil type	Forest age	Average tree height	Average canopy size (east-west)	Average canopy size (south-north)
1	a1、b1、c1	Chestnut soil, sand soil	13a	83	123	113
2	a2、b2、c2	Chestnut soil, sand soil	13a	86	137	104
3	a3、b3、c3	Chestnut soil, sand soil	13a	84	128	108

1.2.2. Measurement of fine root growing rate of H. rhamnoides

Root length density growing rate (*RLD*gr):

$RID\text{gr} = \Delta RLD + (-)/T$

*RID*gr — growing rate, mm cm^{-3} d^{-1};

Δ*RLD* + (-) — biomass increment of fine roots between two adjacent observations, mm cm^{-3} d^{-1};

T— Time interval between two adjacent observations, d.

1.2.3. Measurement of environmental factors

An HOBO small-sized automatic weather station developed by USA was installed in an open space near the forest lands, which collected data at an interval of 10 min. The data were periodically downloaded. The surrounding environmental factors from April to October in both 2018 and 2019 were continuously detected, and the monthly average values were calculated. The environmental factors of interest include X_1: soil moisture content; X_2: soil temperature; X_3: temperature (T_a); X_4: relative humidity (H_R); X_5: vapor pressure deficit (D_{VP}); X_6: photosynthetically active radiation (R_{PA}). Soil moisture content was detected using a neutron moisture meter.

1.3. Data Analysis

Data summarization and plotting were conducted on Microsoft Excel 2016. Data were analyzed on SPSS 26. Significance test of DPS (significance level at 0.05), one-factor analysis of variance (ANOVA), collinearity diagnosis and ridge regression were conducted.

2. Results and Analysis

2.1. Changing Characteristics of Fine Root Growing Rate of *H. rhamnoides*

Both RLD_{gr} after stumping and RLD_{gr} in the control change seasonally with a single peak, and vary within 0.297-1.61 and within 0.214-1.512 mm cm^{-2} d^{-1} respectively (Fig. 2). The RLDgr after stumping peaks to 1.61 mm cm^{-2} d^{-1} in July -August and to 1.512 mm cm^{-2} d^{-1} as early as June -July in the control group. As the weather cools down, RLD_{gr} is affected by the external environmental factors and gradually declines. It drops to 0.524 and 0.274 mm cm^{-2} d^{-1} in September - October in the stumping group and the control group respectivelyThe monthly change of RLD_{gr} in the stumping group is significantly larger than that of the control group, and declines in the control group as early as June - July, which is one month earlier than the stumping group, indicating stumping can effectively promote fine root growth.

In both the stumping group and the control group, RLD_{gr} declines with the narrowing of soil depth (Fig. 3), and decreases the fastest at the depth of 0 - 15 cm, followed by the depth of 15-30 cm, and the root amount decreases as the soil depth increases. At the depth of 0-60 cm, the RLD_{gr} of the stumping group is significantly higher (more than 2 times) than that of the control group, suggesting stumping can promote root activity, and RLD_{gr} in the control group deteriorates. At the depth of 60-100 cm, RLD_{gr} of the stumping group is slightly lower than that of the control group. The reason may be that the trees in the control group are older and more drought-resistant, so the deep roots can utilize water more extensively and are less affected by drought. Namely, deep roots are the major part that plants can depend on under unfavorable environment, and plants with deeper roots can better utilize moisture at deeper soils, which contributes to defending unfavorable growing conditions.

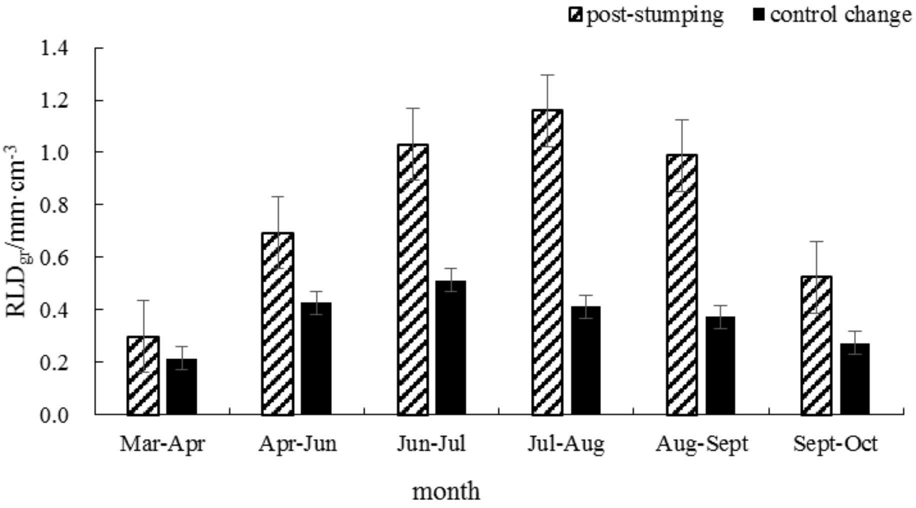

Figure 2. Monthly changing trends of fine root growing rate of *H. rhamnoides* after different treatments

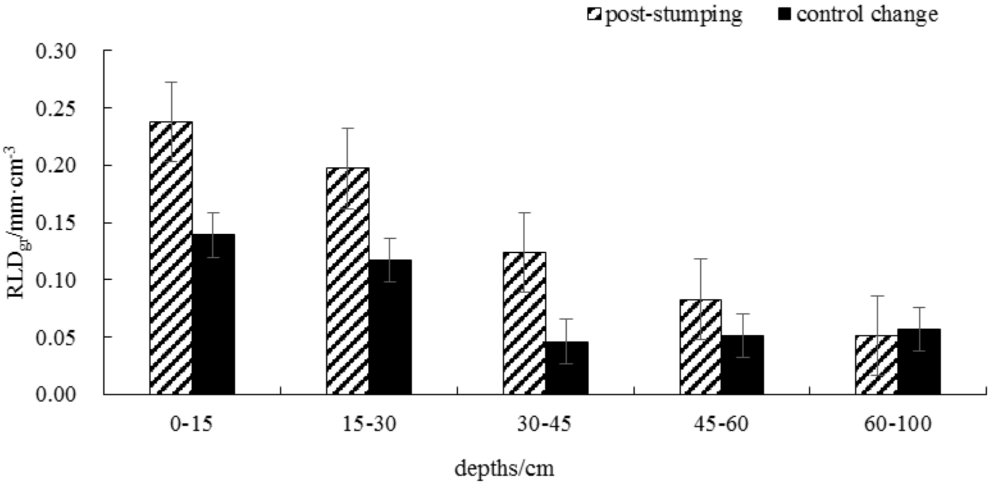

Figure 3. Growing rates of *H. rhamnoides* after different treatments and at different soil depths

2.2. Relationship between Growing Rate Changes of *H. rhamnoides* Fine Roots and Environmental Factors

To visually show the +changes of RLD_{gr} and surrounding environmental factors, we plotted the changing curves of some indicators (soil moisture content, soil temperature, T_a, H_R, D_{VP}, R_{PA}) and RLD_{gr} from April to October.

The seasonal changes of post-stumping RLD_{gr} and soil moisture content both show single-peak, and the changing rate of soil moisture content in feldspathic sandstone areas of Ordos is slightly slower than that of RLD_{gr} (Fig. 4a). The soil moisture content and RLD_{gr} are significantly and positively correlated, as the soil moisture contents in April to August rise from the minimum value of 18.5% to the maximum value of 27.4%, and together with the post-stumping RLD_{gr}, maximize at August. Later, as winter arrives, soil moisture content and RLD_{gr} both drop.

The post-stumping RLD_{gr} and soil temperature in April to October change in similar trends (Fig. 4b). As everything on earth resuscitates in spring and frozen soils gradually thaw, the soil temperature gradually rises since April. After that, fine roots, as the most critical part of the root system to absorb nutrients, are growing along with gradual exploration. Soil temperature maximizes to 22.5 ℃ in August, when RLD_{gr} maximizes too, indicating RLD_{gr} and soil temperature are closely related and inseparable.

Figure 4c shows the changes of post-stumping RLD_{gr} and T_a from April to October. Clearly, post-stumping RLD_{gr} and T_a change in similar trends and are positively correlated. As air temperature rises after the arrival of April, RLD_{gr} and T_a synchronously increase, as the monthly average temperature rises from 5.32 ℃ in April to 23.67 ℃ in August, and maximizes earlier than the maximization of RLD_{gr}. In September as Ta drops, RLD_{gr} gradually decreases.

Figure 4d demonstrates the changing curves of post-stumping RLD_{gr} and HR from April to October. The dynamic changes of H_R and RLD_{gr} are negatively correlated, as RLD_{gr} gradually increases with the decline of H_R. After the arrival of April, as the solar radiation intensity and temperature rise, H_R gradually declines and RLD_{gr} continually increases. The H_R minimizes to 47.69% around August (which drops by 15.18% from May), when RLD_{gr} also minimizes.

Figure 4e shows the changing curves of post-stumping RLD_{gr} and D_{VP} from April to October. As periodic biological phenomena change in the growing season, the monthly average D_{VP} is always low at early stage (April to June) and high at middle and late stages (July to August), and rapidly declines at late stage (September to October). As T_a and H_R change, D_{VP}, as the major driving force of transpiration, rapidly increases at early summer (June), and D_{VP} at the fastest monthly average increasing rate increases by 0.61 kPa. The increasing trend is slowed down in July, and the average D_{VP} maximizes in August (1.81 kPa), and the monthly decreasing rate of D_{VP} is the fastest in September and drops by 45% from August. Hence, the monthly average D_{VP} is positively correlated with RLD_{gr}.

Figure 4f shows the changes of post-stumping RLD_{gr} and R_{PA} from April to October. Clearly, post-stumping RLD_{gr} and R_{PA} change in similar trends and are positively correlated. Thus, R_{PA} minimizes in dry season (April) and maximizes in rainy season (August). Since rainy season there occurs in July - September, the numbers of precipitation and cloudy/rainy days are larger than in other months, and the increasing rate of R_{PA} does not increase largely.

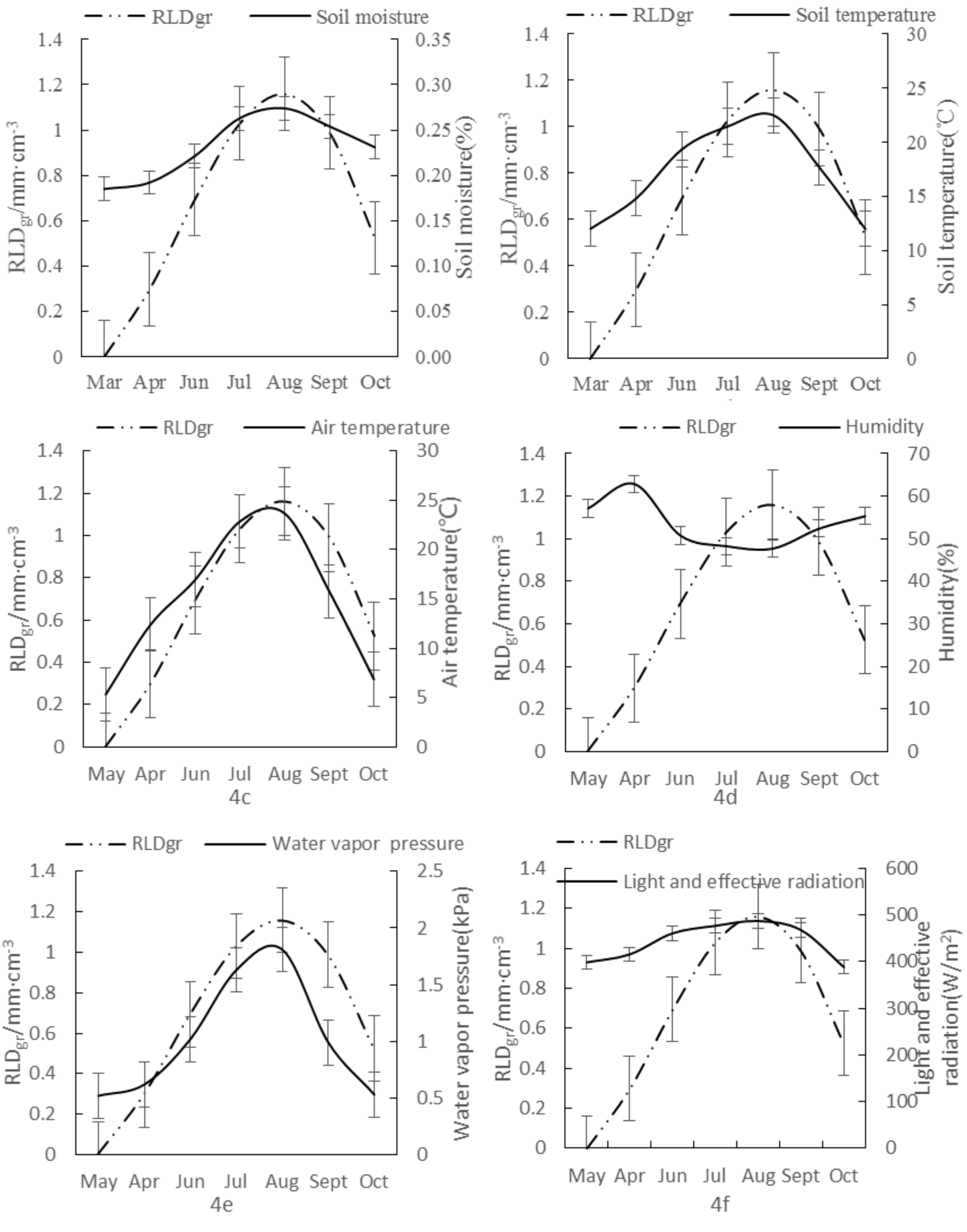

Figure 4. Seasonal dynamics of effects of different environmental factors on growing rate of fine roots

2.3. Regression Analysis between *H. rhamnoides* Growing Rate and Environmental Factors

2.3.1. Construction of multiple linear regression model

RLD_{gr} is affected by the physiological properties of plants, and is closely related to the surrounding environmental factors. Theoretically, the fine root growth of *H. rhamnoides* is largely decided by the effects of surrounding environmental factors. Thus, a regression model of RLD_{gr} is established: with the $RLD_{gr}(y)$ in April to October of both 2018 and 2019 as the dependent variable, and the independent variables included soil moisture content (X_1), soil temperature (X_2), *T*a (X_3), H_R (X_4), D_{VP} (X_5), and R_{PA} (X_6). Firstly, correlations between the dependent variable y and independent variables were analyzed on SPSS. Results show *y* is significantly correlated with X_1, X_2, X_3, X_4, X_5, and X_6, with the correlation coefficients of 0.97, 0.86, 0.88, -0.83, 0.86, and 0.88 respectively. Especially, the correlation coefficent between *y* and X_1 is the largest (0.97). In all, multiple linear regression between *y* and these independent variables is reasonable. The linear regression analysis between *y* and these 6 independent variables is illustrated in Tables 2 and 3. The regression equation is:

$$Y = -3.793 + 12.373X_1 + 0.092X_2 - 0.01X_3 + 0.012X_4 - 0.468X_5 - 2.625X_6$$

According to the fitted modeling results, the determination coefficient R^2 is 0.897, and the adjusted determination coefficient R^2 is 0.862, indicating the fitting effect of this model is excellent. The probability p of the model is 0.0024 <0.05, suggesting this model passes significance test, and the model fitting is valid. The 3 regression coefficients of the regression equation are all negative, which does not accord with actual environmental significance, indicating the regression effect involving all independent variables is not good.

Table 2. Coefficients of variables

Variable factor	Non-standardized regression coefficient	Standardized regression coefficient	Significance level	VIF
(constant)	-3.797		0.0001	
Soil water content	12.388	1.007	0.0003	21.930
Soil temperature	0.093	0.938	0.0124	495.172
T_a	-0.01	-0.175	0.0093	379.610
H_R	0.012	0.156	0.0217	29.149
D_{VP}	-0.469	-0.578	0.0122	23.306
R_{PA}	-2.625	-0.002	0.0092	30.891

Table 3. Single-factor analysis of variance

Source of deviation	Sum of squares	Degree of freedom	Mean square	*F*	Significance
Regression	1.997	6	0.333	5.831	0.05
Residual	0.228	4	0.057		
Total	2.226	10	0.223		

2.3.2. Multicollinearity diagnosis

The variance inflation factors (*VIF*) of the 5 independent variables are 21.930, 495.172, 379.610, 29.149, 23.306, and 30.891 respectively (Table 1). The VIFs of all variables are larger than 10, indicating there is severe multicollinearity among variables. The largest condition number is 495.172, and multicollinearity appears among independent variables. When severe multicollinearity exists among independent variables, the multiollinearity regression model as-obtained is unstable. At this moment, ridge regression analysis may well solve the above problems.

2.3.3. Ridge regression analysis of H. rhamnoides growing rate and environmental factors

The original data were centralized and standardized. In the first regression analysis, the default of ridge parameter k was from 0 to 1, with a step length of 0.01 and totally 101 values.

Ridge regression is defined as:

$$\hat{\beta}(k) = (X'X + kl) - 1\, X'\, Y$$

where X is the designed matrix after standardization; $\hat{\beta}(k)$ is the estimated ridge regression of the regression coefficient vector (appropriate value of k makes the degree of (approaching abnormality smaller than the degree of approaching abnormality).

(1) All 6 independent variables were subjected to ridge regression analysis, forming ridge trace plots (Fig. 5).

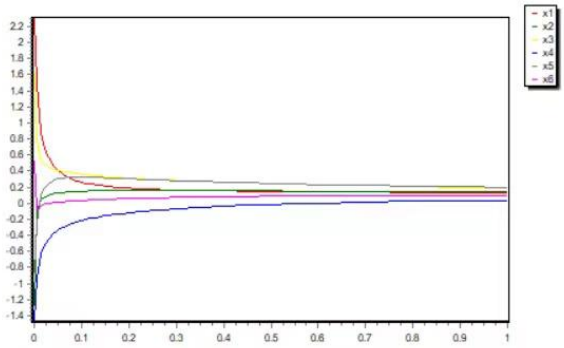

Figure 5. Ridge trace plots of 6 independent variables

(X_1: soil moisture content, X_2: soil temperature, X_3: T_a, X_4: H_R, X_5: D_{VP}, X_6: R_{PA}, X-axis: k value; Y-axis: $\hat{\beta}(k)$)

The ridge trace plots demonstrate that the ridge traces are very chaotic. According to the rule of independent variable selection, firstly, X_6 and X_5, which rapidly approached 0 and had regression coefficients of ridge trace $\hat{\beta}_3(k)$ fluctuating largely, were removed.

(2) After such analysis, 4 variables (X_1, X_2, X_3, X_4) were finally reserved, and then ridge trace plots were drawn (Fig. 6).

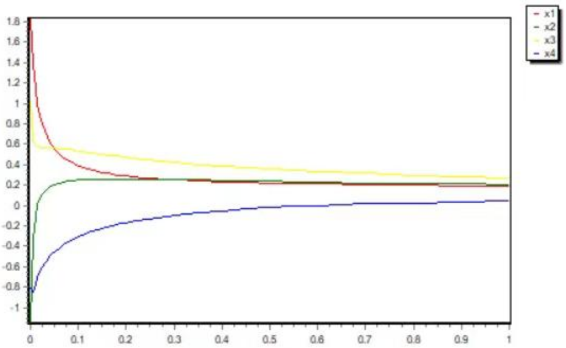

Figure 6. Ridge trace plots of 4 independent variables

The ridge trace plot shows all parameters gradually stabilize after k=0.29. Hence, k=0.29 was chosen, and the corresponding ridge regression estimations were coefficient of multiple determination R^2=0.892, adjusted correlation R^2=0.911, F=14.443, P=0.0017, indicating the fitting effect of the regression equation is excellent, and the coefficients of explaining variables are reasonable.

In all, the ridge regression equation is:

$$y = 0.29 + 0.254X_1 + 0.253X_2 + 0.427X_3 - 0.104X_4.$$

The ridge regression analytical method was used to successfully solve the regression modeling of influence factors on RLD_{gr}. With this method, small deviation was permitted to replace precision above unbiased estimated amount, since it was more probably close to the real value.

3. Discussion and Conclusions

As for the forest germination updating mechanism, Zhu et al. proposed 6 hypotheses [16]. Specifically, the resource allocation hypothesis holds that after the loss of the aboveground part, the resource stored quantity at the roots is very important for tree germination. The variation of RLD_{gr} of *H. rhamnoides* is inevitably related to the stumping height, and appropriate stump height can promote sprout generation and growth and strengthen the root biomass accumulation, thereby accelerating population recovery. Our results indicate RLD_{gr} after stumping is significantly higher than the RLD_{gr} in the control group. Moreover, a regression model with RLD_{gr} as the dependent variable was built, and the independent variables were root soil moisture content (X_1), soil temperature (X_2), Ta (X_3), H_R (X_4), D_{VP} (X_5), and R_{PA} (X_6). Then collinearity was diagnosed. Results show soil moisture content (X_1), soil temperature (X_2), Ta (X_3), and H_R (X_4) are all closely related to RLD_{gr}.

The seasonal dynamic changes of RLD_{gr} are comprehensively affected by the physiological demand for tree growth, the periodic biological properties of roots, and environmental conditions (climate characteristics) [17]. The fine root growth of *H. rhamnoides* is affected by physiological characteristics, and its growth and development are largely impacted by the surrounding environmental factors. Hence, theoretically, the post-stumping RLD_{gr} is largely decided by the surrounding environmental factors of plants.

In arid and semiarid areas with rich solar irradiation, soil moisture becomes a major restricting factor on plant growth, and water deficit results in plant growth and transpiration deceleration, stomata closure, and photosynthetic rate drop [18]. After stumping and cradling, the morphological characteristics including canopy size, plant height and total leaf area all will change, leading to root-canopy ratio unbalance and further affecting site conditions, soil moisture content and periodic variation [19]. Reportedly, soil moisture significantly affects the root systems of *H. rhamnoides* in feldspathic sandstone areas and directly impacts the absorption and migration of soil moisture and nutrients by plants as well as the support to the aboveground part [4]. When soil water and fertilizer conditions are excellent, the root system grows better, and vice versa [20]. This study demonstrates soil moisture content and RLD_{gr} are significantly and positively correlated, and RLD_{gr} increases with the increment of soil moisture and moisture abundance, which are consistent with previous research. Our study area is located in arid and semiarid regions of northwest China, where soil moisture content fluctuates in small amplitude due to low annual precipitation. Bi Jianqi et al. found as long as soil moisture met the growing demand of the root system of *Caragana microphylla*, the root system in low-moisture soils grew better than in high-moisture soils [21]. Hence, we know appropriate drought stress will stimulate the fine roots of *H. rhamnoides* to grow to deeper soils.

Chen Lin et al. found plant phenotype ductility allowed plants to acquire more resources [22,23] and endowed plants with broader ecological sizes and higher tolerance. Plants with higher ductility can better adapt to environmental changes [24]. The environmental responsiveness reflects a balance between internal and external functions of plants during environmental adaptation, and is a key manifestation when plants survive and adapt to specific environment [25]. Our findings offer experimental evidence to this theory. RLD_{gr} increases with the increment of soil moisture content (X_1), soil temperature (X_2), Ta(X_3), D_{VP}(X_5), and R_{PA}(X_6), indicating these environmental factors are pivotal for the variation of RLD_{gr}. At low H_R and high soil moisture content (X_1), soil temperature (X_2), Ta(X_3), D_{VP}(X_5), and R_{PA}(X_6), RLD_{gr} increases. When the limited resources are fully utilized, the plants expand the absorptive extent of roots to occupy more favorable habitats. Thus, *H. rhamnoides* in feldspathic sandstone areas has higher tolerance and better acclimating ability.

Soil temperature and water content both are key environmental factors that affect soil respiration. Normally, soil temperature significantly affects microbe decomposition, root respiration, and enzyme and matrix diffusion, and are thus considered as major controlling factors of soil respiration [26]. In case of moisture deficiency during growth and development of plants, the root respiratory rate drops, and respiration is decelerate with the decrease of moisture, leading to energy supply insufficiency and affecting growth and development. Moreover, moisture deficiency impacts photosynthesis, and the inhibition effect on photosynthesis surpasses that on root respiration [27]. Our study demonstrates that upon the arrival of the peak growth season with temperature rise and rainy season, the activity of soil organic matter is intensified, and RLD_{gr} gradually rises. After the growth peak-season, soil temperature drops, and the root respiratory rate of *H. rhamnoides* is decelerated, and RLD_{gr} declines accordingly. Our findings are consisent with previous studies. Environmental temperature is among the key factors that affect the growth, development, geological distribution, yield and quality of crops. In the face of global climate changes especially the continual temperature rise [28], studying the mechanisms of plants feeling and responding to temperature changes will considerably contribute to global ecological protection, crop stress resistance improvement, and food security guarantee. Reportedly, during plant growth, the majority of intraneous water consumption by plants is derived from transpiration. Ma Xin et al. found solar radiation intensity can directly affect transpiration rate and impacted other meteorological factors [29]. However, meteorological factors including temperature, humidity and solar radiation are dominant factors that affect the transpiration rate. Han Yangrui et al. studied 3 species of typical shrubs in Kubuqi deserts (*Caragana microphylla*, *Salix cheilophila*, *Artemisia ordosica*), and found photosynthesis was an important indicator of plant growth and development and one of the critical physiological characteristics of plants [30]. Plants with strong photosynthesis can accumulate more organic matter to promote plant growth.

In our study, H_{R} in the study area changed in small amplitude within the study period and maintained around 50%. H_{R} minimized in July and August, and was negatively correlated with the root growth of *H. rhamnoides*. Reportedly, high temperature is the cause for the low monthly average H_{R} in summer. H_{R} changes the most severely in winter [31]. In our study, H_{R} is the largest in April and May. A study proves that H_{R} rises in winter and spring [28], which is consistent with our study.

We find the post-stumping RLD_{gr} is significantly correlated with soil moisture content, soil temperature, T_{a}, H_{R}, D_{VP}, and R_{PA} is positively correlated with soil moisture content, soil temperature, T_{a}, D_{VP}, and R_{PA}. Moreover, H_{R} is negatively correlated with RLD_{gr}. RLD_{gr} gradually increases with the drop of H_{R} before August, but changes oppositely after August. The intensity of R_{PA} can induce stoma opening and closure, and directly affects environmental factors, including T_{a} and D_{VP}. Thus, T_{a}, D_{VP}, and R_{PA} are all positively correlated with RLD_{gr}. It is indicated the RLD_{gr} of *H. rhamnoides* fine roots is affected by the surrounding environmental factors, but the influence degrees of the environmental factor differ, and deeper understanding require further research.

Modeling between RLD_{gr} and environmental factors shows that the regression model does not accord with actual situations, as the regression coefficients are unstable. Analysis of VIF demonstrates that the interactions among environmental factors make the regression model inaccurate, so we adopted ridge regression to analyze the independent variables. Through ridge regression, the variables X_5 and X_6 with severe collinearity were rejected, and the resulting ridge regression equation accords with actual situations and the regression equation is stable. Based on analytical results, soil moisture content, soil temperature, Ta, and H_R were selected as fine root explaining variables of RLD_{gr}, and the influence degree on post-stumping RLD_{gr} rank as Ta > soil temperature > soil moisture content > H_R.

Thus, the large RLD_{gr} in July and August may be caused by the high soil moisture content, since to meet the growth demands, fine roots grow massively to absorb moisture and nutrients. When other variables are unchanged, RLD_{gr} rises by 0.254% with the every increment of 1% soil moisture content. When soil temperature, T_{a}, and H_{R} rises by 1%, RLD_{gr} increases by 0.253%, 0.427% and -0.104% respectively.

Ridge regression is different from other methods and can esepcially solve multicollinearity. Regardless of the method used, actual situations must be considered to find out a simple and convenient method to solve practical problems. This method should inconceivably help with analysis of interactions and associations among variables, and can achieve twice the result with half the effort.

(1) The seasonal variation of RLD_{gr} shows a single peak in fall, and RLD_{gr} is the fastest in July and August, which is over 3 times that of Spring, and firstly increases and then declines. RLD_{gr} grows the fastest at the soil depth of 0-15 cm, and decreases with the decline of soil depth.

(2) The post-stumping RLD_{gr} is significantly correlated with soil moisture content, soil temperature, T_{a}, H_{R}, D_{VP}, and R_{PA}, and RLD_{gr} is positively correlated with soil moisture content, soil temperature, T_{a}, D_{VP}, and R_{PA}. Moreover, H_{R} is negatively correlated with RLD_{gr}.

(3) The ridge regression equation between post-stumping RLD_{gr} and environmental factors is $y = 0.29 + 0.254X_1 + 0.253X_2 + 0.427X_3 - 0.104X_4$: where y is the fine root density after stumping (RLD_{gr}), mm cm^{-3}; X_1 is soil moisture content; X_2 is soil temperature; X_3 is Ta; X_4 is H_R. Based on analytical results, soil moisture content, soil temperature, Ta, and H_R were selected as explaining variables of RLD_{gr}, and the influence degree on post-stumping RLD_{gr} ranks as T_{a} > soil temperature > soil moisture content > H_{R}.

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