Response of Belowground Root Growth Dynamics to Snow Cover Change in Alpine Meadows: Postprint

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Abstract

From November 2013 to August 2014, a field control experiment on snow cover amount was conducted in the alpine meadow of Hongyuan County on the eastern edge of the Qinghai-Tibet Plateau using artificial snow accumulation methods. Using natural snowfall as the control (CK), three treatments were established: S1, S2, and S3 (with snow amounts being 2×, 3×, and 4× the natural control, respectively). The minirhizotron method was employed to track and investigate the root growth dynamics of alpine meadow vegetation after snow cover alteration, and the effects of snow cover changes on soil temperature were measured. The results showed that root growth of alpine meadow vegetation exhibited distinct seasonal variations. Over time, root surface area, root tip number, and standing biomass gradually increased and reached maximum values in August-September. When winter snow accumulation reached 143.4 mm (S1), it was most favorable for root growth (with maximum root surface area, root tip number, standing biomass, and production), and the vigorous growth period of roots (with higher net production rates) was advanced and extended. However, as snow accumulation further increased, the positive effect of snow on root growth gradually decreased, and the vigorous growth period of roots was progressively delayed or even disappeared. The study also found that as snow accumulation increased, soil temperature in the 0-10 cm soil layer gradually decreased, and a similar pattern was observed in the 10-20 cm soil layer, albeit with a temporal delay. Correlation analysis indicated that root growth was positively correlated with soil temperature in different soil layers. Therefore, snow cover changes affect the growth and development of plant roots in alpine meadows by altering soil temperature, which may ultimately influence carbon allocation and carbon cycling processes in alpine meadow ecosystems.

Full Text

Response of Belowground Root Growth Dynamics to Snow Cover Change in Alpine Meadow

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Abstract

Permanent or seasonal snow cover is widespread on the Tibetan Plateau. Seasonal snow cover, which is affected by global climate change, is dominant in the northwestern part of Sichuan Province, on the eastern edge of the Tibetan Plateau. The root system is sensitive to environmental change. The effects of seasonal snow accumulation and thawing on soil physicochemical properties and microorganisms could influence the root system in alpine meadow. Understanding the environmental effect on the root system of alpine meadow is essential to better understand the response mechanisms of terrestrial ecosystems to global climate change.

From November 2013 to August 2014, we conducted a field study on controlled snow cover gradients in an alpine meadow of northwestern Sichuan. Four snow cover gradients were established: natural snowpack (control), and snowpack manipulated to be 2-, 3-, and 4-folds that of control. The root growth dynamics of plant communities and their responses to snow cover gradients were continuously monitored using the Minirhizotron method. The effects of the snow cover gradients on soil temperature were also measured.

The results showed that soil temperature decreased with increasing snowpack volume. The optimum root system growth was observed with the natural snowpack. The root growth period was lower in the doubled natural snowpack compared with other treatments at the beginning, but the final root growth was faster than that of the control. Belowground root system growth was restricted in the tripled snowpack. Correlation analysis showed that root growth was positively correlated with soil temperature. Our results indicate that the winter snowpack change directly impacts subsurface ice storage, which in turn affects hydrothermal regimes in the alpine meadow soil and thus root system growth. Belowground root systems may suffer damage when the melt water refreezes underground after infiltrating into the soil and undergoes subsequent freeze-thaw cycles. Overall, moderately increased snowfall is conducive to the growth of the belowground root system, but excessive snow inhibits the belowground root system. Therefore, change in winter snowpack could alter carbon distribution and the carbon cycle in alpine meadow ecosystems.

Keywords: alpine meadow; snowpack change; belowground root system growth dynamics; Minirhizotron method

Introduction

Roots are important organs for plants to absorb nutrients and water, and constitute a vital component of terrestrial ecosystems, playing a significant role in maintaining and improving soil quality. Vegetation root systems exhibit rich ecological diversity in maintaining ecosystem functions. Their belowground distribution patterns and standing crop reflect the allocation patterns of water and nutrients in soil, determine vegetation utilization efficiency and potential for belowground water and nutrients, and represent a core link in ecosystem carbon allocation and carbon cycling. Root systems can promptly perceive and respond to changes in soil microenvironments. Low soil temperature often causes root growth stagnation, while moderately increased soil moisture helps promote plant root growth, whereas insufficient soil moisture leads to suppressed root elongation and reduced branching.

Studying root responses to environmental changes contributes to a deeper and more comprehensive understanding of terrestrial ecosystem response mechanisms to global change. Root ecology has received widespread attention, but traditional methods such as excavation and profile methods involve enormous workload and cause significant damage to roots, largely limiting research on root growth dynamics. The Minirhizotron method, a non-destructive research technique, overcomes these defects and enables repeated in-situ observations of root growth dynamics across multiple time periods, providing convenience for research on root productivity and turnover. With this technology, root ecology has developed rapidly.

The Tibetan Plateau is an important factor affecting the climate pattern of Eurasia and even the globe. Tibetan Plateau ecosystems are highly sensitive to global change, with changes often occurring earlier than in surrounding areas, providing more obvious early warnings of global climate change. In recent years, snow ecology has developed rapidly and gradually become a hotspot field closely related to global change. As a major ecological process under climate change, rapid ice and snow evolution has altered snow conditions in the Tibetan Plateau region. Seasonal snow accumulation and ablation profoundly affect community characteristics, soil physicochemical properties, and soil microbial activity in alpine meadows on the Tibetan Plateau.

In terms of root ecology research on Tibetan Plateau alpine meadows, current studies have focused mainly on warming and succession effects on roots, as well as root distribution in permafrost regions. However, few studies have reported on the effects of snow amount changes on alpine meadow roots. Our research group conducted a snow amount field control experiment in an alpine meadow in Hongyuan County on the eastern edge of the Tibetan Plateau. After snowfall, artificial accumulation was used to establish different snow amounts for plot treatments, and the Minirhizotron technique was used to continuously monitor community root growth dynamics under different snow amounts. This study aims to address the following scientific questions: (1) How does snow change affect root growth dynamics in alpine meadow plants? (2) What mechanisms cause these effects? The results will provide basic data and theoretical support for research on response and adaptation mechanisms of plant community roots in Tibetan Plateau alpine meadows to climate change.

1. Overview of the Experimental Area' s Natural Environment

The study area is located at the Qinghai-Tibetan Plateau base of Southwest Minzu University in Hongyuan County, northwestern Sichuan, with geographic coordinates of 32°49 N, 102°34 E, and an elevation of 3485 m. This region belongs to the plateau area transitioning from the Tibetan Plateau to the Sichuan Basin. The climate type is continental plateau climate, with indistinct four-season changes but distinct dry and wet seasons. The annual average temperature is 1.1°C, annual precipitation is 791.95 mm, annual evaporation reaches 1262.5 mm, annual relative humidity is 60%-70%, and sunshine duration is long with annual sunshine of 2158.7 h and total annual solar radiation of 6194 MJ/m^2. The soil type in the experimental area is alpine meadow soil.

The vegetation growth season in the experimental area runs from May to September each year, with the green-up period concentrated in mid-to-late May. Average vegetation coverage is 45-60 cm, with maximum height reaching 60 cm. Main plant species include the sedge family species *Kobresia setchwanensis* and *Kobresia pygmaea*, the grass family species *Agrostis clavata* and *Elymus nutans*, and forbs including *Anemone trullifolia* and *Saussurea nigrescens.*

2. Experimental Design

2.1 Sample Plot Setup and Snow Amount Field Control Experiment

Sample plots were established in an alpine meadow with relatively uniform terrain and relatively uniform plant distribution within the experimental area. A randomized block experiment design was used to uniformly distribute 2 m × 2 m plots within a 30 m × 30 m area, with at least 1.5 m intervals between plots. Four snow amount treatments were established: CK (natural snowfall), S1, S2, and S3, with each treatment replicated three times.

The snow amount field control experiment was conducted after snowfall. During the experiment period, natural snow amounts are shown in Table 1. CK represents natural snowfall accumulation, while S1, S2, and S3 represent snow amounts of 2×, 3×, and 4× the natural snow amount, respectively. The specific method was as follows: a snow field was established around the sample plots with several waterproof cloths fixed with ground nails. After snowfall, snow on the waterproof cloths was collected and evenly piled into each plot. The accumulation amounts were: all snow from one waterproof cloth for S1, from two cloths for S2, and from three cloths for S3, with buffer zones established between plots.

Snow cover duration in the plots was 14, 17, 19, and 20 days for CK, S1, S2, and S3, respectively, with cumulative snow amounts of 71.4, 143.4, 214.2, and 285.6 mm.

Table 1 Monthly snowfall in the experimental region during the experiment period

Experiment period	Monthly snowfall (mm)

2.2 Soil Temperature Measurement During the snow amount field control experiment, intelligent multi-point soil temperature recorders (YM-01A, Handan, China) were used to measure soil temperature in the 0-10 cm and 10-20 cm soil layers, with measurement accuracy of $±$0.2°C and temperature resolution of 0.01°C.

2.3 Minirhizotron Installation and Data Reading In each treatment gradient, three plots were randomly selected. Following the method of Johnson et al. [28], one minirhizotron tube (7 cm outer diameter, 6.4 cm inner diameter, 100 cm length) was installed in each plot at a 60° angle to the ground, with approximately 60 cm inserted into the soil and about 20 cm exposed above ground. The exposed portion was sealed with a rubber cap and wrapped with tape for waterproofing, then covered with black cloth to prevent light from affecting root growth. Soil drilled out during installation was used to fill around the tube to ensure close contact with soil while minimizing disturbance. When not collecting data, black plastic bags were wrapped around the tubes to reduce heat conduction [29].

Root image data were collected using a CI-600 Root Scanning System (CID Bio-Science Inc., Camas, WA, USA). Each minirhizotron tube was divided into surface soil (0-10 cm) and deep soil (10-20 cm) layers for image collection. The average interval between collections was 16 days.

2.4 Root Data Processing Methods Root analysis software WinRHIZO Tron MF (CID Bio-Science Inc., Camas, WA, USA) was used to obtain root length, root tip number, surface area, and other parameters from the collected images, followed by statistical analysis of the root information.

Following the method of Wu Yibo et al. [30], unit area root standing crop was calculated. Root production was calculated as the difference between final and initial root standing crop measurements. Average root standing crop was the mean of multiple measurements of unit area root standing crop.

Unit volume root length density (RLDv, m/m^3) was estimated from the acquired image data, where L is the root length observed in the minirhizotron window, DOF (m) is the distance from the minirhizotron tube to the surrounding soil (0.003 m in this study), and A (m^2) is the observation window area. Since alpine meadow root diameters are small (<1 mm), 0.003 m was used in calculations. Unit volume root length density was converted to unit area-based standing crop by multiplying by the sampling soil profile depth.

Root net production rate (RLDNGR) was calculated following the method of Wang Mengben et al. [33] with slight modifications:

RLDNGR = (RLDa(n+1) - RLDa(n)) / T

where RLDa is root standing crop (g/m^2), T is the interval days between adjacent observations, and RLDa(n) and RLDa(n+1) are unit area root standing crop in the nth and (n+1)th observations, respectively. A positive RLDNGR indicates root growth rate exceeds death rate, while a negative value indicates death rate exceeds growth rate.

2.5 Statistical Analysis SPSS 20.0 was used for one-way analysis of variance (One-way ANOVA) on root surface area, root standing crop, average root standing crop, and root production among treatments, with least significant difference (LSD) method for multiple comparisons. Pearson correlation analysis was performed between soil environment and root growth status (root surface area, root tip number, and root standing crop). Microsoft Office Fuzzy was used for comprehensive evaluation of root growth status under different snow amounts [34].

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3. Results and Analysis

3.1 Effect of Snow Amount on Root Surface Area In surface soil, root surface area increased uniformly over time, with peak values appearing in late July. CK, S1, and S3 treatments showed peak root surface area on July 20, while S2 peaked on August 5. No significant differences were observed among treatment peaks. CK peak was $(48.20\$\pm9.99)cm^{\{2\},S1was(68.58\pm5.22)cm}\{2\},S2was(72.93\pm9.37)cm^{\{2\},andS3was(70.69\pm9.67)cm}\{2\}\$$. Significance tests showed that S1, S2, and S3 peaks were significantly higher than CK (P<0.05), but S3 peak showed significant differences from other treatments.

In deep soil, CK, S1, and S3 root surface area peaked on July 20, while S2 peaked on August 5. CK, S1, and S3 showed increasing trends before July 20 and decreasing trends afterward. S2 root surface area showed a continuous increasing trend before August 5. CK peak was

(31.98\$±10.24)$cm^{\{2\}, S1was(69.32\pm8.29)cm}\{2\}, S2was(38.84\pm4.79)cm^{\{2\}, andS3was(25.52\pm8.10)cm}\{2\}$\$. S1 peak was significantly higher than other treatments (P<0.05).

Overall, root surface area showed a trend of initial increase followed by decrease with increasing snow amount. S1 treatment showed the greatest root surface area, while S3 showed the smallest, with this trend being more obvious in deep soil.

Figure 1 [**Figure 1: see original paper**] Effects of snowpack volume on the dynamic of root surface area in Alpine meadow

3.2 Effect of Snow Amount on Root Tip Number Root tip number dynamics under different snow treatments showed that in surface soil, CK, S1, and S3 root tip peaks appeared on July 20, while S2 peaked on August 5. CK, S1, and S2 peaks were (535.00\$±72.50), $(536.50\pm76.01), and(547.33\pm68.82), respectively, withnosignificantdiffe$ significantly lower than other treatments (P<0.05).

In deep soil, S3 root tip peak appeared on July 4 [(173.00\$±29.50)], $whileothertreatmentspeakedonJuly20.CK,$ respectively. The changing pattern of root tip number was similar to that of root surface area, showing initial increase followed by decrease with increasing snow amount. S1 treatment had the highest root tip number, while S3 had the lowest.

Figure 2 [**Figure 2: see original paper**] Effects of snowpack volume on the dynamic of root tips in Alpine meadow

3.3 Effect of Snow Amount on Root Standing Crop Root standing crop dynamics under different treatments showed that in surface soil, CK, S1, and S3 peaks appeared on July 20, while S2 peaked on August 5. CK, S1, S2, and S3 peaks were (558.33\$±50.80)$g/m^{\{2\}, (617.47\pm42.75)g/m}\{2\}, (613.33\pm39.41)g/m^{\{2\}, and(413.33\pm39.41)g/m}\{2\}, respecti$

Average root standing crop showed significant differences among treatments. In surface soil, the order was S1 > CK > S2 > S3, while in deep soil it was S1 > S2 > CK > S3, with significant differences among all treatments (P<0.05).

Figure 3 [**Figure 3: see original paper**] Effects of snowpack volume on the dynamic of root standing crop in Alpine meadow

3.4 Effect of Snow Amount on Root Net Production Rate Different snow treatments affected alpine meadow root net growth rate dynamics to varying degrees. In surface soil, root growth remained relatively stable and positive during May 14-31. Positive growth peaks occurred during June 19-July 4 and July 20-August 5. S1 treatment showed relatively stable net growth rate, with peak period on July 4 (9.73 g m^{-2} d^{-1}). S2 vegetation net growth rate showed two positive peaks during the same period (3.00-4.01 g m^{-2} d^{-1}). S3 net growth rate was lower than S1, with peaks of 3.85 g m^{-2} d^{-1} and 4.30 g m^{-2} d^{-1}. CK showed alternating positive and negative growth, with negative growth dominating.

In deep soil, S1 root growth status was relatively stable, maintaining relatively high positive growth during June 19-July 4. S2 root growth peak mainly appeared during July 20-August 5. S3 root net growth rate remained at a relatively low level throughout.

Table 2 Effects of snowpack volume on root net production rate (RLDNGR) in Alpine meadow

3.5 Effect of Snow Amount on Root Production Root production reflects plant community root growth throughout the growing season. In surface soil, root production showed a trend of initial increase followed by decrease with increasing snow amount, with the order from high to low being S1, CK, S3, S2, with significant differences among all treatments ($P<0.05$). In deep soil, root production showed the same trend, with the order being S1, S2, S3, CK, with significant differences among all treatments ($P<0.05$).

Figure 4 [**Figure 4: see original paper**] Effects of snowpack volume on the mean root standing crop in Alpine meadow

Figure 5 [**Figure 5: see original paper**] Effects of snowpack volume on root production in Alpine meadow

3.6 Comprehensive Evaluation of Snow Amount Effects on Root System Using the membership function method in fuzzy mathematics, a comprehensive evaluation was conducted on the degree of influence of different snow amounts on plant roots. In surface soil (0-10 cm), the degree of snow amount influence on plant roots from high to low was S2 (0.897), S1 (0.881), CK (0.562), and S3 (0.281). In deep soil (10-20 cm), the order was S1 (0.737), S2 (0.468), CK (0.162), and S3 (0.058). Comprehensive evaluation of both soil layers showed the overall influence degree was S1 > S2 > CK > S3.

Table 3 Function value of subordination and result of comprehensive judgment on root characteristics under different snowpack volume treatments in Alpine meadow

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4. Correlation Analysis Between Soil Temperature and Root Growth

4.1 Soil Temperature Changes Under Different Snow Treatments Snow amount change significantly affected soil temperature in different soil layers. From November 2013 to March 2014, surface soil temperature (0-10 cm) generally decreased with increasing snow amount. As temperatures gradually warmed from March to August 2014, differences in surface soil temperature among treatments gradually decreased. In March 2014, soil temperature differences among different treatments were significant ($P<0.05$).

In deep soil (10-20 cm), there were no significant differences in soil temperature among treatments in November 2013. From December 2013 to March 2014, soil temperature showed a trend of initial decrease followed by increase with increasing snow amount, with significant differences among treatments (P<0.05). From April to July 2014, soil temperature decreased with increasing snow amount, with significant differences among treatments (P<0.05). In August 2014, there were no significant differences in soil temperature among treatments.

Figure 6 [**Figure 6: see original paper**] Effects of snowpack volume on the dynamic of soil temperature in Alpine meadow

4.2 Correlation Analysis Between Soil Temperature and Root Growth

Correlation analysis showed that in surface soil (0-10 cm), soil temperature was significantly positively correlated with root standing crop, root surface area, and root tip number (P<0.05). In deep soil (10-20 cm), soil temperature showed positive correlations with root growth status, but not reaching significant levels.

Table 4 Pearson correlation between soil temperature and vegetation root growth under different snowpack volume treatments

5. Discussion

As snow is a poor heat conductor with low thermal conductivity and large heat capacity, it can affect energy balance and influence soil temperature through processes such as water evaporation. Snow cover depth, snow layer density, and snow cover duration all strongly affect soil freezing rate during the freezing period and soil warming during the melting period. Snow cover in winter prevents soil heat loss, keeping soil temperature higher than air temperature, while in spring it prevents soil temperature from rising, delaying the warming time.

In this study, despite air temperatures below 0°C, the high thermal radiation level on the Tibetan Plateau still caused rapid snowmelt, shortening snow cover duration and greatly reducing snow’ s insulation effect on the ground. After snowmelt, water infiltrated into the ground and quickly refroze to form underground ice, which effectively prevented surface water and soil moisture from percolating downward, causing underground ice to accumulate in the soil surface layer. Due to high daytime thermal radiation and large diurnal temperature differences on the Tibetan Plateau, underground ice underwent repeated freeze-thaw cycles, during which the ice layer gradually moved downward. Different underground ice storage amounts also changed the duration of repeated freeze-thaw processes and the rate of ice layer downward movement.

The same pattern was delayed in the 10-20 cm soil layer. Surface soil temperature (0-10 cm) decreased with increasing snow amount, while deep soil temperature (10-20 cm) also decreased with increasing snow amount. After underground ice gradually disappeared, vegetation status became the main factor determining soil temperature changes among different treatments.

As an important component of terrestrial ecosystems, root growth and development are closely related to the rhizosphere environment. Soil temperature and moisture directly control root growth and development. Temperature increase is beneficial for root growth and development, while low temperature stress leads to restricted root growth or even damage. Our results show that snow amount change significantly affected soil temperature during the growing season. As snow amount increased, soil temperature gradually decreased. Different snow amounts also had significant effects on root growth status.

When snow amount reached 143.4 mm (S1), root growth was optimal, with maximum root surface area, standing crop, and production. When snow amount reached 214.2 mm (S2), root growth period was delayed, but final growth status was still slightly better than control. When snow amount reached 285.6 mm (S3), belowground root growth was inhibited. Correlation analysis showed that root growth was positively correlated with soil temperature in different soil layers, similar to results reported by Pregitzer et al. [50].

Some studies suggest that underground ice melt and snowmelt produce water beneficial for vegetation green-up. However, excessive soil ice content and low soil temperature conditions are detrimental to plant root growth. During early growing season, meadow plants have relatively low water demand but high temperature requirements. The negative effects of underground ice melt and snowmelt on soil temperature recovery must indirectly affect plant and root growth. During the repeated freeze-thaw process of frozen soil layers caused by special climate conditions on the Tibetan Plateau, melting causes significant leaching and freezing causes strong physical damage, both of which affect root growth and survival, as do indirect effects on soil microorganisms [52-53].

Soil temperature, moisture, and other environmental factors jointly determine alpine meadow plant root growth status. These factors often have synergistic or antagonistic relationships. Different winter snow amounts created different environmental effects, altering soil environments in different periods and affecting alpine meadow plant root growth status. Within a certain period, multiple environmental factors jointly created a favorable environment for root growth. When snow amount reached 143.4 mm (S1), it may have been most conducive to root growth. As snow amount further increased, soil environment gradually became unfavorable for root growth. When snow amount reached 285.6 mm (S3), negative effects may have become dominant, inhibiting root growth.

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6. Conclusion

Winter snow amount change altered soil temperature, thereby affecting root growth dynamics of alpine meadow plant communities. Our results show that as snow amount increased, 0-10 cm soil temperature gradually decreased. The same pattern occurred in 10-20 cm soil layer, but with temporal delay. When winter snow amount reached 143.4 mm (S1), it was most conducive to root growth, with maximum root surface area, standing crop, and production, and the vigorous growth period was also advanced and extended. As snow amount further increased, the positive effect of snow on root growth gradually decreased, and the vigorous growth period was gradually delayed or even disappeared.

Correlation analysis showed that root growth was positively correlated with soil temperature in different soil layers. These results indicate that snow amount, to a certain extent, controls soil temperature during the growing season in alpine meadows, thus affecting root growth and development of vegetation communities, and may ultimately affect carbon allocation and carbon cycling processes in alpine meadow ecosystems. However, increased snow amount affects not only soil temperature but also soil moisture and structure. Whether changes in soil moisture and structure cause changes in root growth dynamics requires further research.

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