Gap thinning improves soil water content, changes the vertical water distribution and decreases the fluctuation
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Abstract

Although it is clear that gap thinning significantly increases the soil water content (SWC) of the topsoil, less is known about whether and how this treatment affects deeper layers. From December, 2008 to April, 2012, we monitored the SWC at the depths of 10, 20, 30, 45, 60 and 90 cm in gap creation treatments (small gap size of 30 m$^2$, intermediate gap size of 80 m$^2$, and unthinned plots) in a typical pine plantation in the eastern Tibetan Plateau. Among gap treatments, differences in SWC and the coefficient of variation of SWC (CV) at each depth, and the soil water content proportion (SWCP) of the whole soil profile at specific depths were compared. Gap thinning improved SWC and decreased the CV at each depth. The SWCPs in thinned plots were lower at the depths from 10 to 30 cm compared to those in unthinned plots, but higher at the depths of 45 and 60 cm. And at each season, the patterns were similar to the general results. In conclusion, gap thinning improves the SWC, changes the vertical soil water distribution and decreases the SWC heterogeneity. The soil water conditions in intermediate gaps are more appropriate for local forest restoration.

Key words: gap size, precipitation, season, soil layer, understory plant
Introduction

Forest gap thinning is an effective protocol to improve understory environmental conditions, thereby contributing to seedling establishment and increasing species diversity (Muscolo et al. 2014). Soil water content (SWC) is one of the crucial factors which reflect the land-atmosphere interaction (Rambo and North 2009), regulate soil nutrient (Hu et al. 2016), respiration (Pang et al. 2013) and microbiological activity (Yang et al. 2017), affect fine root dynamics (Železnik et al. 2016) and play a significant role in the growth and regeneration of understory vegetation (Beedlow et al. 2013). Former studies have revealed that the SWC in gaps were generally higher than those under the canopy (e.g. Latif and Blackburn 2010). This is because gap thinning reduces the canopy interception and enables more access for the precipitation to the forest floor (Wang et al. 2012). Moreover, elimination of trees reduces the extraction of water by belowground roots (Marthews et al. 2008) and the transpiration of trees is also decreased (Ritter et al. 2005). However, most of the previous works only investigated the SWC at relatively shallow soil depths (≤ 25 cm) (e.g. Scharenbroch and Bockheim 2007), and less is known about the responses of SWC to gap thinning at deeper soil layers and how they differ from those at shallow soil depths, which may distract us from accurately understanding the effects of gap thinning on the reestablishment and succession of the understory vegetation community because plants from different groups have inherently varied root distribution across shallow and deeper soil layers (Stahl et al. 2013). Besides, most of the former studies based their conclusions on monthly or seasonal SWC observations, but these less chronologically sufficient evidences may obscure the dynamic variation patterns (Liancourt et al. 2012). Therefore, long-term and continuous SWC monitoring at deeper soil layers (including the whole root distribution soil layer) is
needed to deepen our knowledge on the spatiotemporal effect of gap thinning on the forest soil, and to serve as a basis for further investigation on the succession of understory species and their eco-physiological adaptation after gap creation (Wang et al. 2013).

The gap size controls the above- and blow-ground soil drying process and thus determines the SWC (Marthews et al. 2008). Previous studies have investigated differences in SWC among different-sized gaps (both natural and artificial). Studies by Latif and Blackburn (2010) in a temperate broadleaved deciduous forest (gap sizes from 40 to 286 m$^2$), and Gebhardt et al. (2014) in Norway spruce forest (from unthinned control to heavily thinned plots with basal area reduction of 67 %) suggested that the SWC increased significantly with the gap size. In contrast, He et al. (2012) indicated that the SWC decreased as the gap size grew (from 100 to above 400 m$^2$) in the subtropical evergreen broadleaved forests. Nonetheless, Gálhidy et al. (2006) found the soil moisture was independent of the gap size (approximately from 80 to 1250 m$^2$) in a Hungarian beech forest. Due to varied local climates and vegetations, the thinning intensities should be different and thus specific research is needed to guide the practical treatment.

Even though it is clear that forest gap thinning improves the SWC, the SWC in gaps tends to decline as the gap ages due to the growth and regeneration of understory plants (Gray et al. 2002). For example, Ferreira et al. (2004) found the differences in SWC between control and gap treatments disappeared after 7.5-8.5 years in the tropical upland forest. In the same vein, Ritter et al. (2005) reported that although gap creation significantly improved the SWC in the first year, the difference was less clear in the second year. On the other hand, Gebhardt et al. (2014) found the thinned plots still showed substantial surplus in soil water compared with the unthinned plots after
three years. Moreover, the effects may vary in relation to specific seasons. Ritter et al. (2005) found that the soil in gap was wetter than in control in summer, but the difference was not significant in winter in the forest dominated by semi-natural beech in Denmark. On the other hand, Zhu et al. (2007) demonstrated that the gap possessed greater SWC throughout the whole year in a montane secondary forest in China. Temporal dynamics of SWC after gap thinning are estimated to be affected by many factors such as soil texture, forest type, regional environmental conditions, the growth and regeneration of understory plants (Pan et al. 2015), and vary from place to place. More investigations on the temporal variations of SWC after gap thinning are therefore needed to expand our knowledge about the effects of this forest management treatment from a different angle, predict the dynamic trends and guide local gap creation scientifically.

To evaluate the effects of gap thinning on understory SWC, from 2008 to 2011 (right after the gap creation), we monitored the SWC at six soil depths (10, 20, 30, 45, 60 and 90 cm) in a typical temperate pine plantation in the eastern Tibetan Plateau. The water content proportion of the whole soil profile at each depth (SWCP) and the coefficient of variation of SWC (CV) were calculated. Differences in SWC, SWCP and CV at each soil depth among varied gap treatments were compared. We aim to answer the following questions: 1. How gap thinning affects the SWC, SWCP and CV at different soil depths? 2. How the above parameters differ among gap thinning treatments as a function of different seasons? We hypothesize that gap thinning will significantly improve soil water conditions.
Materials and Methods

Study area and experimental design

The field work was undertaken at the thinning experimental site of a 30-years-old Chinese pine (Pinus tabulaeformis) plantation near the Maoxian Mountain Ecosystem Research Station of Chinese Academy of Sciences in Maoxian County, Sichuan, China (103°54' E, 31°42' N, 1826 m asl). The region has a typical temperate climate with an annual sunshine time of 1373.8 h, an annual mean temperature of 9.3 °C, annual precipitation of 825.2 mm and annual evaporation of 968.7 mm. Treatment plots were designed as control, small gap and intermediate gap with vertical projected gap areas of 0, 30 and 80 m², respectively (each treatment has three replicates, with a total of three control and six gap plots) on similar blocks (Fig. S1, Supplementary material is available at Canadian Journal of Forest Research online) (Zhao and Bao 2016). We set the largest gap area at about 80 m², because most of the natural forest gaps in the local pine plantation were smaller than 80 m², and a large forest gap would increase the risks of landslides and soil erosion. At the end of the 2008 growing season, the mean diameter at breast height of the trees was 15.4 cm, with a mean height of 11.2 m (Pang et al. 2013). In 2013, the mean diameter at breast height and the mean height of the gap-edge trees became 17.7 cm and 12.5 m, respectively. The mean values of photosynthetically active radiation, air temperature and humidity at soil surface were significantly higher in intermediate and small gap plots than those in control plots (Wang et al. 2015).

Regional environmental condition monitor and SWC data collection

Regional climate factors, including air temperature and precipitation, were obtained
using automated Vaisala Milos 520 weather station (about 1500 m away from the
study site), with one-hour observation interval (Vaisala 2001). SWC was measured
every five days during the growing seasons (April to October) and every ten days
from November to March, which started on December 01, 2008 and ended on April
22, 2012. Three calibrated neutron probe tubes (CNC 503B Hydroprobe; Beijing
Super Power Company, Beijing, China) were installed at the centre, upper and lower
gap edges along the contour in each plot (27 tubes in total for three treatments, nine
study plots). According to the observation of the soil profile, we found the roots of the
understory shrub and herbaceous plants were mainly distributed at the depth above 30
cm, trees above 60 cm, and the soil gravel content obviously increased at the depth
deeper than 100 cm. Thus, six depths (10, 20, 30, 45, 60 and 90 cm) were chosen. The
measurements were conducted manually between 9 and 11:30 am in the absence of
raining. The volumetric SWC (θ, %) at each depth was calculated with slowing
neutron counting rates (CR), using the following linear calibration curves:

$$\theta = 50.21 \times CR + 8.50 \quad (R^2 = 0.911; \quad 0-20 \text{ cm})$$ (1)

$$\theta = 61.19 \times CR - 0.70 \quad (R^2 = 0.921; \quad 20-100 \text{ cm})$$ (2)

The SWCP (to indicate the vertical water distribution) for each measurement was
calculated as the SWC at each depth divided by the sum of SWC of the six depths.

Data analysis

We averaged the data obtained from the three neutron probe tubes in each study plot
per measurement as raw data for analysis. The CV was calculated as the ratio of
standard deviation to the mean value, using all of the raw data at each depth in each
study plot. Firstly, differences in SWC, SWCP and CV among gap treatments and soil
depths were compared using the ANOVA test and LSD method was used to perform pairwise comparisons among varied groups (nonparametric independent sample test and Kruskal-Wallis method was used when distribution was not normal). Secondly, based on previous climatic monitoring (Yin 2007), we categorized the measurement time into four seasons [Winter (December-February), Spring (March-May), Summer (June-August) and Autumn (September-November). Only the SWC data that spanned whole seasons were used for analysis (winter, four periods from Dec., 2008 to Feb., 2012; spring, summer and autumn, three periods each, from 2009 to 2011)] (Fig 1). At each soil depth, SWC, SWCP and CV were averaged for each season, and the differences in these parameters among gap thinning treatments in specific seasons were compared. Finally, we summed up the daily precipitation of the day of SWC measurement and 4-day antecedent daily precipitation as the precipitation data (corresponding to each SWC raw data), and averaged the mean daily temperature of the SWC measurement day and 4-day antecedent temperature as the temperature data. Spearman correlation was used to explore the relationships among SWC at each soil depth, regional precipitation and air temperature data. Statistical analyses were performed using PASW Statistics 18.0 (IBM, NY, USA) and Microcal Origin 9.0 (Northampton, MA, USA). All values were considered significant when \( p \leq 0.05 \).

**Results**

The SWC in gap plots were all significantly higher than those in control at all depths (by 4.7% to 44.2%) (Fig 2). At 10 and 60 cm soil depths, the intermediate gaps possessed higher SWC than those in small gaps (Fig 3a). No significant differences were found between the two gap treatments at the depths of 20, 30 and 45 cm. The SWCP in control sites were higher than those in gaps at the depths of 10, 20 and 30
cm, while the results were reversed at the depths of 45 and 60 cm (Fig 3b). The CV in gap plots were generally lower than those in control except at the depth of 90 cm (Fig 3c).

At any soil depths, the SWC in gap plots were significantly greater than those in control in each season and throughout the three years after gap creation (Figs 1 and 4). The patterns of SWCP and CV at each depth in each season were similar to the general patterns (Table S1 and S2).

The SWC were positively related with precipitation in the depths from 10 to 90 cm at small and intermediate gap plots, whereas significant correlations were observed only at the depths of 10, 20 and 30 cm in control (Table 1). Moreover, the temperatures were negatively associated with the SWC at 10 and 20 cm in control, but positively related with the SWC at 60 and 90 cm in the small gap and 30, 45, 60 and 90 cm in the intermediate gap.

Discussion

_Gap thinning improved the SWC, changed the distribution pattern and reduced the fluctuation_

Our results demonstrated that gap thinning significantly improved the SWC in the whole soil profile, and this effect can last at least three years in the current site (Figs 2, 3a). The significant correlation between SWC and precipitation at the depths from 45 to 90 cm in gaps, but not in control sites, implies that gap thinning permits the precipitation water to penetrate to deeper soil layers (Table 1). Changes in SWC over time after gap creation is a complex multistep process, associated closely with the growth and regeneration of understory plants (Gray et al. 2002).
The change in water distribution along soil profiles (SWCP, 10-30 cm: control > gap; 45-65 cm, control < gap) (Fig 3b) is attributed to the fact that the elimination of tree canopy results in faster soil surface evaporation (which mostly affects the results at 10 cm), and greater amounts of water are extracted by the newly emerged forest floor plants (unpublished data, Yan, see Table S3). Therefore, the gap thinning may lead the roots of the forest floor plants to grow downwards to deeper layers due to hydrotropism (Eapen et al. 2005). Furthermore, the lower heterogeneities of SWC in thinned plots than those in control is because the precipitation is more accessible to the soil (improving the water input amount), while the water uptake by belowground roots decreased (reducing the water output) (Fig 3c).

The relatively higher SWC in intermediate gaps than those in small gaps at the depths from 10 to 60 cm (Fig 3a) might be that in a small gap, the soil drying in the center of the gap is controlled by the roots of the surrounding trees (the roots of Pinus tabulaeformis are mainly distributed at the depths from 0 to 60 cm) (Liu et al. 2007), the evaporation from soil surface and water uptake of understory plants. However, in a larger gap, the trees at the forest gap edge are located further from the center, so their roots are less likely to extend to this area and have smaller effects on water extraction in the gap center (Pang et al. 2016).

**Comparison of SWC, SWCP and CV in specific season**

The differences in SWC at each depth and SWCP between thinned plots and control were similar in each season, and are identical to the overall patterns shown above, indicating that the effects of gap thinning on SWC and water distribution along the soil profile are seasonally independent (Figs. 3, 4, Table S1). Specifically, due to varied study regions and local climates, our result was different from that of Ritter et
(2005) (which found no significant differences among gap treatments in winter). It could be argued that the precipitation is mainly in the form of snow in the current site in winter (Fig. 1), thus the gap thinning creation actually leads to an increase of the forest-floor temperature, and permits the snow to melt and soak into the soil. Besides, the CV in gaps were generally lower than those in control, but the differences were not always significant at each depth and in each season. In summer, the lower CV in control plots in the whole soil profile might be that the trees grow fastest in this season and have the greatest demand for water. In contrast, in winter, the differences in CV were significant at 20 and 30 cm, but not at 10 cm, due to the fact that the annual shrub and herbaceous in winter were very scarce. Thus although the water is more likely to penetrate and store in soil layer in gaps, the evaporation of the soil surface was also higher as compared to the control plots with tree canopy.

Conclusion

Our research indicates that gap thinning significantly increases the SWC at the whole soil profile in the current study site, changes the vertical water distribution patterns and decreases the SWC heterogeneity. Moreover, the differences remain at all seasons, and throughout the first three years. Hence we suggest that soil water conditions in intermediate gaps (approximately 80 m²) are more appropriate than in smaller gaps for future thinning practice. This work reveals a comprehensive and detailed SWC temporal dynamic pattern after gap creation, contributes to a scientific gap thinning treatment for forest restoration, and provides the basis for further studies on soil respiration, microbiological succession and the regeneration of understory plants. A longer-term monitoring research, especially coupled with the understory growth and regeneration, is still needed, by which we can show a complete picture of SWC
dynamic along the understory succession after gap thinning.

Acknowledgement

We thank Dr. Xiaoli Yan, Dr. Qingxia Zhao, Dr. Fanglan Li, Dr. Xiaozhen Pu and Dr. Fu Chen for providing background data and suggestions. We also thank the anonymous reviewers for their valuable comments. This work was supported by the National Key R&D Program of China (2017YFC0505002), the National Natural Science Foundation of China (31770658) and the Key R&D Program of Sichuan Province (2017SZ0038, 18ZDYF0307), and the Sino-German Postdoc Scholarship Program (57165010) of China Scholarship Council and German Academic Exchange Service.

References


Table
Table 1 Spearman correlations between regional environmental factors (precipitation and air temperature) and soil water content at six soil depths in three gap thinning treatments in a pine plantation forest in Maoxian County, Southwestern China.

<table>
<thead>
<tr>
<th>Environmental factor</th>
<th>Gap treatment</th>
<th>Soil depth (cm)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>90</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td>Control</td>
<td>0.337**</td>
<td>0.235**</td>
<td>0.176*</td>
<td>0.120</td>
<td>0.100</td>
<td>0.090</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Small</td>
<td>0.375**</td>
<td>0.346**</td>
<td>0.261**</td>
<td>0.215**</td>
<td>0.207**</td>
<td>0.241**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>0.449**</td>
<td>0.439**</td>
<td>0.352**</td>
<td>0.325**</td>
<td>0.248**</td>
<td>0.248**</td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>Control</td>
<td>-0.161*</td>
<td>-0.145*</td>
<td>-0.090</td>
<td>-0.020</td>
<td>0.100</td>
<td>0.130</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Small</td>
<td>-0.020</td>
<td>-0.050</td>
<td>-0.030</td>
<td>0.130</td>
<td>0.255**</td>
<td>0.340**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>0.100</td>
<td>0.090</td>
<td>0.209**</td>
<td>0.257**</td>
<td>0.317**</td>
<td>0.380**</td>
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</tr>
</tbody>
</table>

The number of samples is 195 at each soil depth in each gap thinning treatment.

Asterisks indicate the significance level (2-tailed): *, \( p \leq 0.05 \); **, \( 0.001 \leq p \leq 0.01 \); *** \( p < 0.001 \).
Figure legends

Figure 1

Variations of regional precipitation and air temperature from December, 2008 to April, 2012, in Maoxian County, Southwestern China. Bars represent the precipitation and dots indicate the temperature. Different fill colours for both bars and dots indicate the season division [white: winter (December-February), light grey: spring (March-May), dark grey: summer (June-August) and black: autumn (September-November)].

Figure 2

The temporal variations in soil water content (mean ± standard error) at different depths in the control and two thinning treatments in the pine plantation in Maoxian County, Southwestern China. The measuring period was from Dec. 1, 2008 to Apr. 22, 2012. Each data point of soil water content is a mean of three measurements.

Figure 3

Changes of soil water content (mean ± standard error, a), soil water content proportion (b) and mean coefficient of variation (c) at six soil depths (0-90 cm) in response to gap thinning treatments in a pine forest plantation in Maoxian County, Southwestern China. Capital letters indicate the differences among varied soil depths and lowercase letters indicate the differences among treatments. Bold letters denote the soil water content in intermediate gap. Each data point of soil water content is a mean of 585 measurements.

Figure 4

Seasonal patterns of soil water content (mean ± standard error) in response to gap
thinning treatments in six soil profiles in a pine forest plantation in Maoxian County, Southwestern China. Lowercase letters indicate the differences among treatments. The measurements at each soil profile in each gap thinning treatment is 108 for winter (Dec.-Feb.), 135 for spring (Mar.-May), 162 for summer (Jun.-Aug.) and 180 for autumn (Sep.-Nov.), respectively.
Fig 1

58x42mm (300 x 300 DPI)
Fig 2

333x653mm (300 x 300 DPI)
Fig 3

126x93mm (300 x 300 DPI)
Fig 4

114x76mm (300 x 300 DPI)