Forest Ecology and Management 401 (2017) 273–285

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Temporal variability in soil moisture after thinning in semi-arid *Picea crassifolia* plantations in northwestern China

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ARTICLE INFO

Article history:
Received 7 April 2017
Received in revised form 12 July 2017
Accepted 13 July 2017
Available online 21 July 2017

Keywords:
Soil moisture
Spatio-temporal dynamics
Soil hydrological response
Picea crassifolia plantations
Qilian Mountains

ABSTRACT

Soil moisture controls the functioning of semi-arid ecosystems. The response of soil moisture to forest stand thinning determines planting density and sustainability of forest development. However, consequences of stand thinning are poorly known in semi-arid ecosystems of the Qilian Mountains of China. We investigated long-term effects of three thinning intensities in *Picea crassifolia* plantations on soil hydrological responses and soil moisture dynamics at 10, 20, 40, 60, and 80 cm depths, and compared them to those of a natural *Picea crassifolia* forest.

Results revealed that soil hydrological response may be temporarily modified by thinning according to changes in canopy structure, precipitation properties, and antecedent soil moisture conditions. Soil moisture in natural forest rapidly infiltrated into deep soil, which greatly improved the efficiency of precipitation use. Thinning significantly increased the capacity for soil infiltration, and moderate thinning intensity may be conducive to deep soil-water recharge. Soil moisture content changed drastically after thinning, with a significant decrease near-surface (10 cm), and a significant increase in sub-surface (60 and 80 cm) soil. High planting density was the main cause of severe soil moisture deficits in the long-term, but it could be mitigated by 20–40% thinning (~3139 trees ha^{-1}). Changes in precipitation patterns that include larger but less frequent rainfall events during the growing season will benefit the growth of vegetation planted at high densities in this semi-arid region.

1. Introduction

Grassland afforestation is critical in efforts to prevent widespread land degradation in arid and semi-arid regions of China (Chen et al., 2008a; Yang et al., 2014), where rainfall is the main source of soil moisture, and where many vegetation restoration projects were implemented (Li, 2004). However, soil moisture is the most crucial factor to sustainability of planted forests in these water-limited ecosystems (Newman et al., 2006; Yang et al., 2014). Soil moisture constrains plant transpiration and photosynthesis, thereby affecting the water, energy, and biogeochemical cycles of the land surface (Western et al., 1999; Seneviratne et al., 2010; Trancoso et al., 2016). In turn, soil moisture is also affected by vegetation (Zou et al., 2008). In forested ecosystems, canopy structure can profoundly influence soil water content mainly by rainfall interception, moisture uptake for transpiration, and shading of the forest floor which affects sub-canopy microclimate and evaporative drying of soil (Breshears et al., 1998; Schrumpf et al., 2011; Chang et al., 2014; He et al., 2014). Changes to forest canopy structure due to large-scale harvesting may lead to changes in soil properties, residual tree growth, and the mean and the variance of the soil moisture (Chen et al., 1993; Olchev et al., 2009; He et al., 2013; Kaarakka et al., 2014). Thinning has been an important, commonly-used silvicultural strategy in forest ecosystems in China and other regions, especially for plantation management (Selig et al., 2008; Nave et al., 2010; Chase et al., 2016). This silvicultural practice opens the forest canopy, and changes light penetration, temperature, and moisture at ground level (Chase et al., 2016). Such changes result in modifications in understory plant diversity and community composition (Thomas et al., 1999; Dodson et al., 2008), canopy interception (Schrumpf et al., 2011), soil infiltration rate (Tarpey et al., 2008; Wall, 2012; Chen et al., 2014), and water balance (Gutiérrez-Jurado et al., 2006; Gebhardt et al., 2014). Alterations in both biotic and abiotic variables following thinning can modify soil moisture dynamics and soil hydrological response in forest ecosystems, which in turn have the potential to affect forest

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http://dx.doi.org/10.1016/j.foreco.2017.07.022
0378-1127/

productivity, eco-hydrological processes, and ecosystems function (Gebhardt et al., 2014; Chase et al., 2016).

Soil moisture varies greatly in both space and time because it is controlled by factors such as atmospheric dynamics, soil properties, vegetation characteristics, and topographic features (Miller et al., 1983; Western et al., 1999; Gómez-Plaza et al., 2001). Precipitation patterns are among the most important factors influencing the spatial and temporal variability in soil moisture in high-mountain areas (He et al., 2012). Therefore, changing precipitation regimes will affect soil moisture variability, which may influence terrestrial ecosystems by affecting plant growth (Lindroth et al., 1998). Recently, global circulation models predicted a shift in precipitation patterns, with larger but less frequent rainfall events in many areas of the world during the growing season, and more frequent extreme hydrological events around the world (Easterling et al., 2000; Alpert et al., 2002; Heisler-White et al., 2008; Trenberth, 2011; IPCC, 2013; Wang et al., 2013). Large precipitation events are important for water storage within the soil profile, and Heisler-White et al. (2008) showed that large rainfall events increased soil water content and facilitated moisture penetration deep into the soil profile of a semi-arid grassland in northeastern Colorado, USA. He et al. (2012) found that soil moisture of the grassland and meadow ecosystems in surface layers responded quickly to rainfall events, but it responded increasingly slowly with increasing soil depth; further, large rainfall events (>20 mm) played a key role in soil water storage of the grassland and meadow ecosystems in Qilian Mountains. Sun et al. (2015) also found that the sensitivity of soil moisture response to rainfall differed depending on land cover and soil depth, and fluctuation in soil moisture diminished with increasing depth in the Qilian Mountains. They further pointed out that soil moisture under alpine shrub-land was far more sensitive to individual rainfall events, whereas other land-cover types needed periods of frequent rainfall to exhibit a typical response (Sun et al., 2015).

Numerous findings on the effects of thinning on soil moisture dynamics and soil hydrological response are available in the literature, including changes in soil water storage, seasonal soil water content, and spatial and temporal variability of soil moisture at different scales (Chen et al., 1993; Zou et al., 2008; Schrumpf et al., 2011; He et al., 2013). However, extensive uncertainty remains about the eco-hydrological consequences of thinning, and the results vary greatly with climate, forest type and age, soil type and depth, thinning type and intensity, and the time since thinning (Selig et al., 2008; Nave et al., 2010; Kaarakka et al., 2014). For example, some studies of the soil water content in Ponderosa pine forests at different densities reported higher soil water contents in low than in high density stands (Feeney et al., 1998; Stone et al., 1999; Zou et al., 2008), while others reported no differences (Sala et al., 2005), or differences in one year but not in another (Simonin et al., 2006). Still other studies showed that relatively large-scale forest clearings led to a higher level of soil water content due to reduced interception and transpiration rates in areas without trees (Bruijnzeel, 2004; Schrumpf et al., 2011). Conversely, increased solar radiation levels due to low-density canopies may enhance soil evaporation and promote fast growth of secondary or understory vegetation, both of which can accelerate the depletion of soil moisture (Bhatti et al., 2000; Giambelluca, 2002). Although some researchers found that the effect of transpiration appeared to be greater than interception effects, no consistent conclusions have been drawn about the contribution of thinning to soil moisture dynamics (Zou et al., 2008; Schrumpf et al., 2011; He et al., 2013; Gebhardt et al., 2014). Thus, long-term monitoring data are needed from stands with different levels of thinning to increase the understanding of the eco-hydrological consequences of grassland afforestation.

The Qilian Mountains, located in the northern margin of the Tibetan Plateau, are the source of three key inland rivers in northwestern China, including the Heihe, Shiyang, and Shule. The mountains were designated as a National Nature Forest Reserve in 1988 for their key role in maintaining regional ecological security. Forests, dominated by the Qinghai spruce (*Picea crassifolia*), and grasslands, dominated by *Elymus cylindricus* and *Achnatherum splendens*, are the main landscape types in this area (Wang et al., 2001). *Picea crassifolia* is a shade-tolerant species growing in locations with annual precipitation of approximately 400–700 mm. It is hardy, and tolerates cold and dry climate, and poor soil conditions. Trees can grow up to 35 m in height, and longevity is reported to be 250 years (Chen et al., 2012). Water storage capacity of forests in the Qilian Mountains amounts to approximately 552 million m^3 (Che et al., 1992). However, due to deforestation and climate conditions, forest cover of this forest type decreased from 22.4% in 1949 to 12.4% during the latter part of the 19th century (Wang and Cheng, 1999). In recent decades, with the implementation of projects National Forest Conservation Program, "Grain for Green" program, and others, the area of planted vegetation in the Qilian Mountains has increased significantly (Li, 2004), and many semi-arid grasslands were converted to *Picea crassifolia* plantation forests (He et al., 2012).

However, without the scientific background and sustainable management technology, soil degradation/desertification, low forest productivity, and poor stability of the ecosystem are common problems in the afforested areas (Chen et al., 2008b; Nagaike et al., 2012). Improving the stability in this system, and alleviation of soil drought are of great importance to the sustainable management of plantation forests (Cao et al., 2011). To reduce water deficits and to increase stem-level productivity, silvicultural thinning (whole-tree harvesting) has been a major form of forest management for *Picea crassifolia* plantation forests in the Qilian Mountains (Zhu, 2015). However, little research has been conducted to determine changes in soil hydrological response and soil moisture dynamics with the different thinning intensities in plantations and natural forests. An understanding of the response of soil moisture at different depths to thinning has important implications, especially for choosing sustainable planting density in semi-arid regions. Thus, the objectives of the present study were to elucidate the changes in soil hydrological responses, to analyze changes in soil moisture dynamics in plantation forest stands under different thinning intensity, and compare soil moisture variability in thinned stands with that in undisturbed natural forests. Our goals were to understand the changes in soil hydrological response and soil moisture dynamics, and to determine whether thinning management can effectively improve the state of soil moisture in the subalpine *Picea crassifolia* plantations in the Qilian Mountains.

2. Materials and methods

2.1. Site description

The study site (center at 38°32.597′N, 100°15.277′E) was located approximately 60 km southeast of Sunan Yugur Autonomous County, Gansu Province, in northwestern China, and within the Guantai forest protection zones in the middle of the Qilian Mountains. The site has a semiarid and cold temperate climate, with a mean annual temperature of about 2.5 °C and mean annual precipitation of about 385 mm (mean value from years 1994 to 2014), about 80% of which falls mainly between June and September. The mean annual evaporation is from 1569 to 1788 mm, and the average annual sunshine duration is 1895 h (Zhu et al., 2015). Gray cinnamon soil, present on shaded slopes, and chestnut soil, developed on sunny slopes, are the two most typical soils in this catchment (Chen et al., 2015). The approximate start and end of the growing season in the region are in late May and early September, respectively. Native vegetation patterns are closely related to topographic aspects, and represent a mosaic of grassland, forest, and small areas of scrubland (He et al., 2012). Forests, dominated by *Picea crassifolia*, are distributed on shaded, north-facing slopes. Common species in the understory layer include shrubs such as *Potentilla glabra*, *Potentilla fruticosa*, *Berberis kansuensis*. Herbaceous species, such as *Carex atrata*, *Achnatherum splendens*, *Oxytropis kansuensis*, and *Medicago archiducis-nicolai*, are mainly found on sunny, south-facing, and semi-shaded, east- or west-facing slopes.

Since the 1980s, most of the grasslands on semi-shaded slopes had been converted into *Picea crassifolia* plantation forests (for details, see Zhu et al., 2017). The vast, recently afforested areas had a high stand density around 4500 trees ha^{-1}, and contained a limited number of *Larix principis-rupprechtii* Mayr trees (around 210 trees ha^{-1}). In the spring of 2006, timber harvesting in the form of thinning was undertaken on this site. The harvest was carried out manually. The thinning aimed to remove poor-growing trees as well those lacking vigor.

2.2. Study design and data collection

In the study, north-facing slopes were defined as shaded, south-facing slopes were defined as sunny, southeast-facing or south by southwest-facing slopes were defined as semi-sunny, and northwest-facing slopes or northeast by north-facing slopes defined as semi-shady (Zhu et al., 2017). In early August 2013, a survey was carried out in the *Picea crassifolia* plantation and in the nearby natural *Picea crassifolia* stand, which at the time of sampling were 31 and 48 years, respectively. The age of the stands was determined by interviewing landowners and by taking increment cores from several trees. Selected stands had similar site conditions. Included in the survey were: an unthinned stand with 4458 trees ha^{-1} (HD), a 20% thinning with 3558 residual trees ha^{-1} (MD), a 40% thinning with 2721 residual trees ha^{-1} (LD), and a no thinning natural forest with 1652 trees ha^{-1} (NF). Detailed site descriptions are shown in Table 1. Natural forest was located near the plantation forests (with a Euclidean distance of <1 km), and the unthinned stand had not received any management since planting. Three replicate sample plots of $30 \times 30\ m^2$ were randomly located in each plantation stand and natural forest for a total of 12 sample plots; plots were spaced at least 20 m apart to avoid edge effects. Geographic coordinates and elevations of each plot were obtained using a global positioning system (GPS) with differential correction.

Within each plot, diameter at breast height (DBH), tree height, and the number of trees were measured. The herbaceous layer and mosses were harvested in ten randomly-located quadrats of $1 \times 1\ m^2$, and collected samples were oven-dried at 80 °C to a constant weight to measure the aboveground biomass of understory vegetation. Five randomly-located soil profiles were excavated for each plot (after removing of the surface litter layer), and soil samples were collected at the depths of 0–10, 10–20, 20–40, 40–60, and 60–80 cm for soil chemical analyses. Soil pH was determined using the method of acidity agent (soil-water ratio of 1:5) (PHS-3C pH acidometer, China) (Deng et al., 2014). Soil organic carbon (SOC) was determined by the colorimetric method following digestion with sulfuric acid and potassium dichromate at 5% (Anderson and Ingram, 1993). Total nitrogen (N_{tot}) was determined using the Kjeldahl procedure involving digestion with sulfuric acid (Jackson, 1968). In addition, undisturbed soil cores were obtained from each layer for the measurements of soil bulk density using a standard container with the volume of $100\ cm^3$ (Blake and Hartge, 1986).

2.3. Measurements of soil water content

In each of the HD, MD, LD, and NF plot, a soil pit with the dimension of $1.0\ m \times 1.0\ m \times 0.8\ m$ was dug and equipped with soil moisture/temperature probes (5TM systems). The 5TM systems consisted of five integrated volumetric water content and temperature ECH2O sensors permanently deployed at depths of 10, 20, 40, 60, and 80 cm to monitor soil water content and temperature, and the 5TE/5TM sensors were coupled with a CR 1000 data logger (Decagon Devices Inc. Pullman, WA, USA). The range of soil volumetric moisture content was from 0 to 100% with accuracy of ±2% in any porous medium, and the operating environment of soil temperature change for 5TM systems was from −40 to 60 °C with 0.1 °C accuracy. After the 5TE/5TM sensors installation, soil pits were filled back with the original soil material, compacted to bulk density, and covered with the leaf litter that was removed before digging. Soil water content was also measured every 30 days by oven-drying to validate the soil water content data provided by the probes during the study period. After each sample, the soil was backfilled and the surface was flattened. Data were collected over a four-year period in the NF and HD stands, and over a two-year period in MD and LD stands. The 80-cm data from the NF stand were not available for the 2014 and 2015 growing seasons due to the volumetric water content and temperature ECH2O sensors at this layer were damaged.

Soil water storage for each soil layer was calculated using the following equations (Zhu et al., 2015):

$$VSWC_i = SWC_i \times B_i \quad (1)$$

$$SWS_i = VSWC_i \times D_i \quad (2)$$

where SWS_i is the soil water storage (mm), SWC_i is the gravimetric soil water content (%), $VSWC_i$ is the volumetric soil water content (%), B_i is the soil bulk density ($g\ cm^{-3}$) and D_i is the soil thickness (mm) at layer *i*.

Table 1
Geographical and stand characteristics of the *Picea crassifolia* plantation and adjacent natural *Picea crassifolia* forest stands. Values (±SE) followed by different lower-case letters within rows are significantly different at $P < 0.05$.

Forest type	Thinning treatment[b]	Altitude (m)	Slope (°)	Aspect (°)	Stand density (trees ha^{-1})	Plantation age (yr)	DBH[a] (cm)	Height (m)	Aboveground biomass of mosses ($g\ m^{-2}$)	Aboveground biomass of herbs ($g\ m^{-2}$)
Plantation	HD	2787	11.6	344.8	4458 ± 41	32	7.9 ± 0.16a	6.2 ± 1.21a	614.31 ± 45.23a	2.5 ± 4.5a
	MD	2821	12.1	336.3	3558 ± 52	31	8.2 ± 0.13b	6.4 ± 1.32b	274.50 ± 28.58b	85.47 ± 8.53b
	LD	2816	10.7	327.5	2721 ± 55	30	8.6 ± 0.18b	6.8 ± 1.48b	50.33 ± 21.98c	116.53 ± 10.94c
Natural	NF	2800	14.5	338.5	1652 ± 95	48	10.6 ± 0.16c	7.9 ± 1.03c	249.85 ± 35.64b	28.49 ± 12.49d

[a] DBH is diameter at breast height.
[b] NF represents the natural *Picea crassifolia* forest, HD, MD, and LD represent *Picea crassifolia* plantation forest stands of unthinned, 20% thinned, and 40% thinned, respectively.

2.4. Measurements of precipitation

An Environmental Integration System (ENVIS, IMKO Micromodultechnik GmbH, Ettlingen, Germany) was installed in a grassland at 2800 m with a Euclidean distance of <1 km to the natural and plantation forest sites to monitor climatic conditions, including air temperature, humidity, solar radiation, rainfall, wind velocity, and soil moisture and tension in soil layers at 20, 40, 60, 80, 120, and 160 cm (for details, see Liu et al., 2007). Additionally, a conventional ground meteorological observation field for long-term observations, about 50 m away from the ENVIS. Meteorological variables, such as precipitation, air temperature, relative humidity, sunshine duration, wind speed, atmospheric pressure, surface temperature, pan evaporation, and depth of soil freezing was manually recorded at 8:00, 14:00 and 20:00 daily.

To compare hydrological responses of the different soil layers in HD, MD, LD, and NF, several maximum daily rainfall events (including July 20th (30.8 mm), July 30th (29.7 mm), August 10th (25.3 mm), and July 4th (30.5 mm) in 2012, 2013, 2014, and 2015, respectively) were selected.

2.5. Growing seasons

Soil water content varies during the growing seasons due to the strong interaction with vegetation, and tends to stay constant during winters due to snow cover and negligible root activities (He et al., 2013). The period during which the monthly mean temperature is above 5 °C is often used to define the growing season (Takahashi et al., 2003). Based on that, the growing season at our study sites extends from June to September. We focused on analyzing water dynamics in the growing seasons, specifically, during 2012–2015 in NF and HD, and during 2014–2015 in NF, HD, MD, and LD.

We divided the four seasons in our study area, i.e., spring (March to May), summer (June to August), autumn (September to November) and winter (December to February). Precipitation, temperature, and mean soil moisture content were also determined for March to May, June to August, September to November, and December to February to represent the conditions of the monitoring sites (NF, HD, MD, and LD) in spring, summer, autumn, and winter, respectively.

2.6. Statistical analysis

All data were expressed as mean ± standard error. We used one-way analysis of variance (ANOVA) to examine the differences among HD, MD, LD, and NF stands in canopy characteristics, soil properties, volumetric soil moisture content (VSWC), and soil water storage (SWS). The least-significant-difference test (LSD) was used when significant differences were detected by ANOVA, and significant differences were evaluated at the 0.05 level. All statistical analyses were performed using the software program SPSS, ver. 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Characteristics of rainfall events and stand habitats

The annual precipitation averaged 401.51 ± 45.60 mm during the study period, with 71.6–87.3% falling during the growing season (Fig. 1a and b). The highest mean monthly precipitation in years 2012–2015 was observed in July, at 110.18 ± 33.77 mm (Fig. 1b). Rainy days accounted for 41–54% of the growing season. Daily rainfall of <5 mm accounted for 20.6–23.4% of total rainfall, and 62–66% of the total rainy days during the growing season.

Tree DBH and height, and aboveground biomass of herbs in all plantation stands tended to increase, while aboveground biomass of mosses tended to decrease with the increase in thinning intensity (Table 1). NF had the largest tree DBH and height of all stands, and DBH and height in HD were significantly lower than those in LD. However, no significant differences were observed in DBH and height between MD and LD.

Generally, SOC and N_{tot} in all sampled soil depths tended to decrease with increased thinning intensity, while soil bulk density tended to increase. Soil bulk density in the 0–40 cm layers in LD was significantly higher than that in HD (Table 2). NF had the largest SOC and N_{tot} values, but the smallest soil bulk density of all stands; SOC and N_{tot} in the upper soil layer (0–40 cm for SOC, and 0–20 cm for N_{tot}) in HD were significantly higher than those in LD. Thinning was also associated with an increase in soil pH in the 0–20 cm soil, and the soil pH in these layers in MD and LD were significantly higher than that in HD.

3.2. Changes in soil hydrological response

Generally, soil moisture at 10 cm depth in all stands responded to rainfall events first; then, there was a lag effect following a rainfall event, especially in soil moisture in deep layers. However, due to the differences in canopy structures, antecedent soil moisture conditions, and precipitation properties, there were marked changes in soil hydrological responses in stands with different thinning levels and in the natural forest stand. At the NF, the surface (10 cm) soil moisture rapidly infiltrated into the 20 and 40 cm depths, thus improving the efficiency of precipitation utilization for soil and stand. Thinning significantly changed the soil hydrological response, and moderate intensity thinning facilitated the recharge of the deep soil water as compared to the NF (Figs. 2and 3).

During the two consecutive large rainfall events with a short dry interval, soil moisture at the depth of 10 cm and 20 cm in all stands except for the 20 cm soil layer in HD, both exhibited a double "spike" (Fig. 2). When two large rainfall events with a short time interval and high rainfall intensity occurred (July 16th, and July 20th 2012), soil moisture at 40-cm depth in NF also displayed a double "spike", while HD had only a single "spike" (Fig. 2a). However, when two large, but low intensity rainfall events with a dry interval occurred (July 2th, and July 4th 2015), soil moisture at 40-cm depth in NF did not exhibit the double "spike" (Fig. 2b). Soil moisture at 80-cm depth in NF increased significantly when two consecutive rain events totaled >60 mm with a short dry interval and high rainfall intensity; at the same time, soil moisture at 80-cm depth in HD did not have a significant response (Fig. 2a). Soil moisture at 60-cm depth in NF, MD, and LD increased significantly when two consecutive, low intensity rain events had a total rainfall of >50 mm with a short dry interval (Fig. 2b).

Following extreme precipitation events, soil moisture at the depth of 10, 20, and 40 cm in all stands, except for the 40 cm soil layer in HD, exhibited a significant response (Fig. 3). With the small rainfall events before an extreme precipitation event, soil moisture content at 60-cm depth in NF and MD had a significant response, however, at 80-cm, only NF had a significant response (Fig. 3a). Without the small rainfall events before an extreme precipitation event, only MD had a significant response at the depth of 60 cm; however, at 80 cm, there was no significant response in any of the stands (Fig. 3b).

3.3. Changes in soil moisture dynamics

3.3.1. Inter-annual changes in soil moisture during the growing season

The temporal dynamics of the VSWC and precipitation profiles for the four stands are shown in Fig. 4. Individual stands displayed

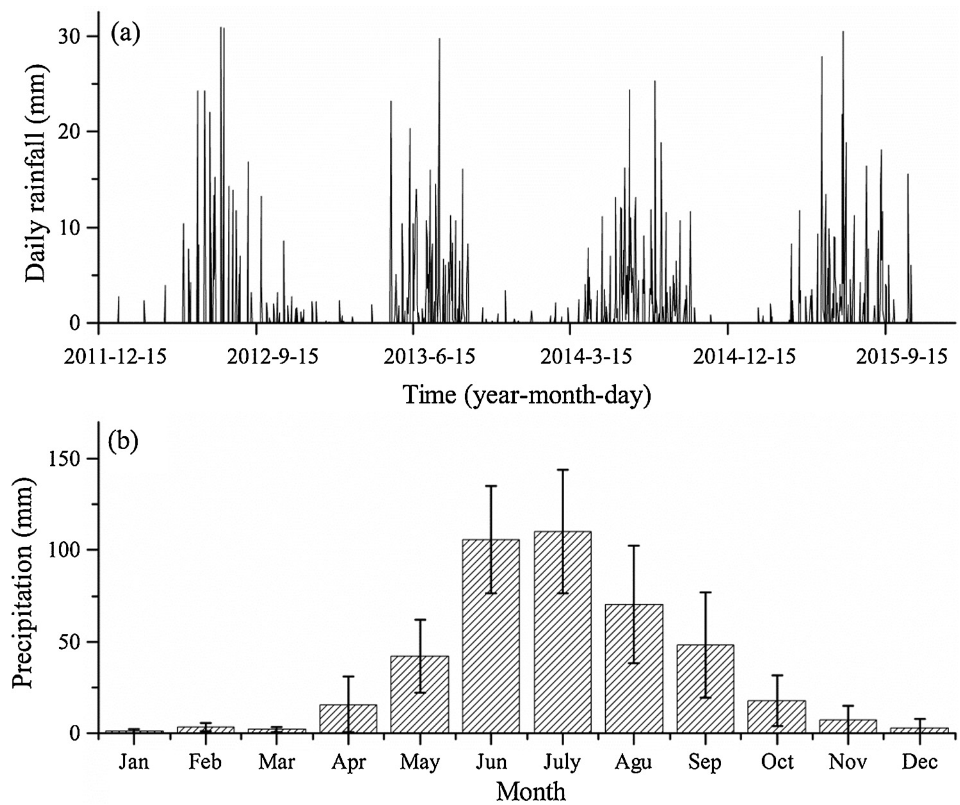

Fig. 1. Daily rainfall and mean monthly precipitation at the study sites.

Table 2
Comparison of soil bulk density, soil organic carbon, soil total nitrogen, and soil pH among different thinning treatments and soil layers. Values (±SE) followed by different lower-case letters within rows are significantly different at $P < 0.05$.

Soil property	Soil depth (cm)	HD	MD	LD	NF
Soil bulk density (g cm^{-3})	0–10	0.78 ± 0.08 d	0.83 ± 0.03 c	0.93 ± 0.04 b	0.71 ± 0.02 a
	10–20	0.90 ± 0.03 c	0.92 ± 0.08 c	0.97 ± 0.03 b	0.74 ± 0.03 a
	20–40	0.89 ± 0.04 c	0.94 ± 0.02 c	1.01 ± 0.04 b	0.81 ± 0.04 a
	40–60	0.92 ± 0.05 b	0.93 ± 0.04 b	0.98 ± 0.03 b	0.83 ± 0.02 a
	60–80	0.98 ± 0.04 b	0.96 ± 0.05 b	1.01 ± 0.02 b	0.95 ± 0.04 a
Soil organic carbon (g kg^{-1})	0–10	72.63 ± 5.02 a	63.03 ± 4.14 b	50.33 ± 4.52 c	90.53 ± 6.05 d
	10–20	66.83 ± 3.75 a	53.57 ± 3.95 b	44.52 ± 3.10 c	75.62 ± 4.72 d
	20–40	51.58 ± 5.42 a	46.56 ± 3.83 ab	41.61 ± 2.51 b	64.54 ± 5.32 c
	40–60	40.95 ± 2.65 a	39.26 ± 3.40 a	35.50 ± 2.98 a	50.25 ± 2.95 b
	60–80	34.14 ± 3.64 a	30.98 ± 2.00 a	29.36 ± 1.76 a	41.23 ± 3.21 b
Soil total nitrogen (g kg^{-1})	0–10	4.38 ± 0.20 a	4.02 ± 0.39 ab	3.56 ± 0.21 b	4.95 ± 0.24 c
	10–20	4.25 ± 0.13 a	3.61 ± 0.29 b	3.30 ± 0.10 b	4.56 ± 0.17 c
	20–40	3.54 ± 0.31 a	3.37 ± 0.20 a	3.12 ± 0.18 a	3.89 ± 0.36 b
	40–60	2.85 ± 0.24 a	2.80 ± 0.16 a	2.77 ± 0.21 a	2.95 ± 0.24 b
	60–80	2.36 ± 0.30 a	2.25 ± 0.15 a	2.22 ± 0.08 a	2.56 ± 0.20 b
pH value	0–10	7.40 ± 0.06 c	7.55 ± 0.07 b	7.64 ± 0.05 b	7.85 ± 0.09 a
	10–20	7.73 ± 0.07 c	7.90 ± 0.07 b	7.93 ± 0.06 b	8.01 ± 0.05 a
	20–40	7.93 ± 0.06 b	7.95 ± 0.04 b	8.02 ± 0.07 b	8.21 ± 0.07 a
	40–60	8.28 ± 0.05 a	8.23 ± 0.06 a	8.30 ± 0.06 a	8.35 ± 0.06 a
	60–80	8.44 ± 0.04 a	8.49 ± 0.09 a	8.46 ± 0.03 a	8.50 ± 0.04 a

noticeable differences in VSWC. During the 2012–2015 growing season, HD always had the highest VSWC of all stands at 10 cm depth ($p < 0.05$), with an average values of 0.23 ± 0.04, 0.26 ± 0.02, 0.27 ± 0.03, and 0.26 ± 0.03 $cm^3\ cm^{-3}$, respectively. However, VWSC in NF in each layer except at 10 cm depth, was higher than in other thinning stands. In NF, loss by canopy interception was 35.1 ± 20.7% of gross precipitation (He et al., 2014), but in HD, it was 40.55 ± 14.79% (Zhu, 2015). The average VSWC at 60 and 80 cm depths was significantly higher ($p < 0.05$) in NF than in other thinning stands. During the 2012–2015 growing seasons, VSWC in HD at 60 and 80 cm depths was, respectively, only 64.4 and 66.1% of the VSWC in NF at the same depth. During the 2014–2015 growing seasons at 60 cm depth, the order of VSWC for the four sites was NF > MD > LD > HD; and VSWC in HD, MD, and LD was only 64.6, 84.2, and 81.1% of VSWC in NF at the same depth. At 80 cm, VSWC had the same ranking as 60 cm depth, and VSWC content in HD, MD, and LD was only 66.7, 75.6, and 87.6% of the VSWC in NF at the same depth.

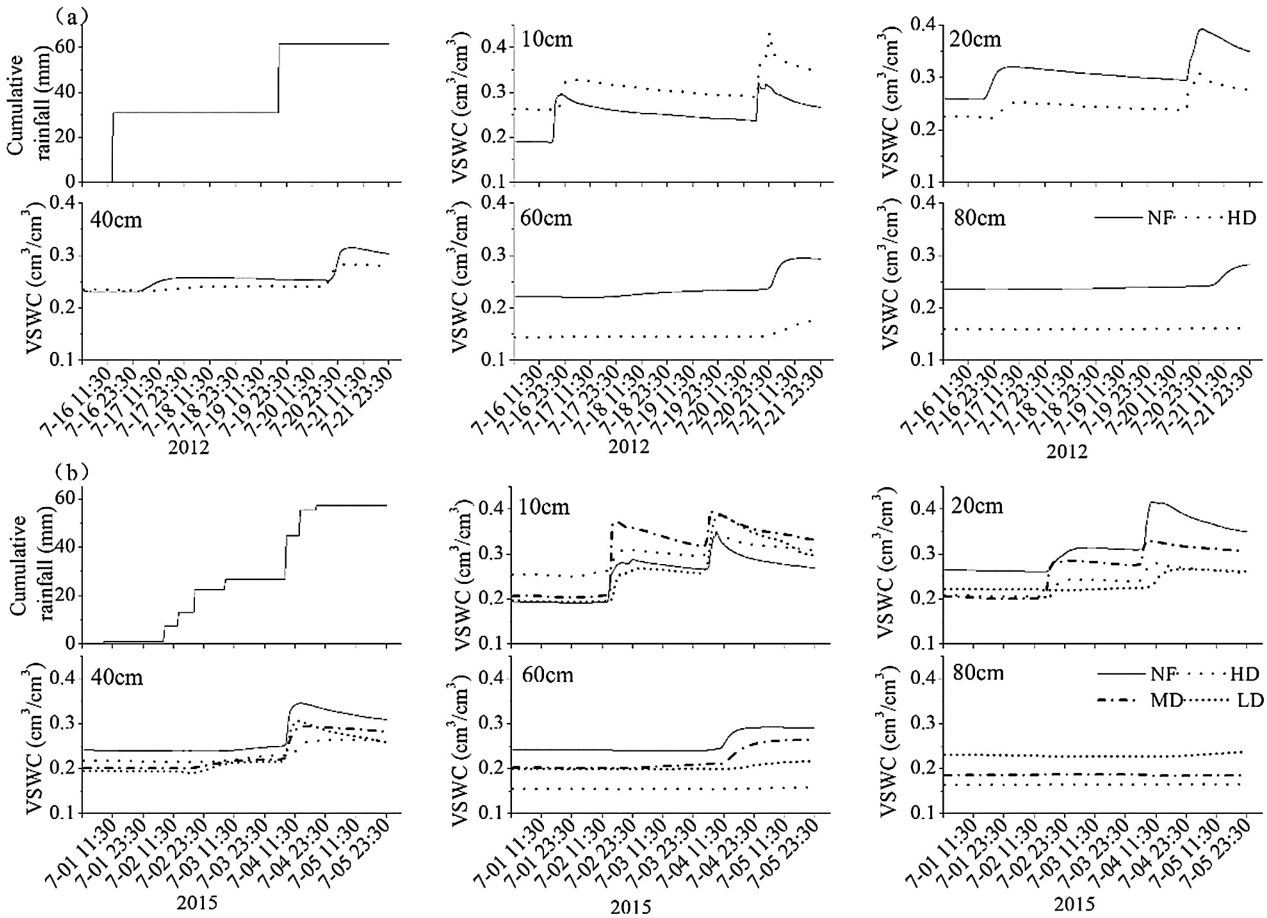

Fig. 2. The response of soil moisture in the NF, LD, HD, MD, and LD to two large (>20 mm) consecutive rainfall events during the 2012 and 2015 growing seasons.

3.3.2. Soil water storage and vertical changes in soil moisture during the growing season

The VSWC profile characteristics of different stands during the 2012–2015 growing season are displayed in Fig. 5. The mean VSWC at the 0–80 cm depth in HD, MD, LD, and LD were 0.201 ± 0.021, 0.209 ± 0.026, 0.212 ± 0.016, and 0.243 ± 0.024 $cm^3 cm^{-3}$, respectively (Table 3). The annual average VSWC did not differ significantly between MD and LD, but both were significantly different from those in NF and HD ($p < 0.05$); the trend of VSWC across the stands was NF > LD > MD > HD. The trend of VSWC at 10 cm depth was HD > MD > NF > LD; at the deep layers (60 and 80 cm), however, the trend of VSWC was NF > LD > MD > HD (Table 3). Soil moisture content changed drastically after thinning, with a significant decrease near-surface (10 cm), and a significant increase in sub-surface (60 and 80 cm) soil. During the study period, SWS oscillated above or below a mean value (Table 4), and the mean differed for the four stands. The mean values were 156.55 ± 12.58 mm in HD, 165.20 ± 14.91 mm in MD, 169.07 ± 10.11 mm in LD, and 194.69 ± 15.35 mm in NF. SWS at the 0–80 cm depth accounted for the following percentages of the SWS in NF: 79.7% in HD, 84.9% in MD, and 86.8% in LD.

3.3.3. Seasonal changes in soil moisture

Time series of VSWC (0–80 cm) showed a similar seasonal pattern (although with different amplitudes) across NF, HD, MD, and LD (Fig. 6). The most precipitation occurred in summer with 286.38 ± 31.70 mm rain, accounting for 67.17% of rain in the four seasons, and the total seasonal amount of precipitation events ranked as: summer > autumn > spring > winter. Seasonal changes of the VSWC for each layer in all stands corresponded with the seasonal changes in precipitation. At 10 cm depth, HD had the largest VSWC, and it was significantly different than that in other stands ($p < 0.05$); except for the VSWC at 10 cm depth, however, VSWC in NF for the four seasons was significantly greater than that of other stands ($p < 0.05$). In summer, VSWC at 60 and 80 cm depth was ranked as: NF > LD > MD > HD, with significant differences between stands (except for MD and LD at 60-cm depth). In autumn, VSWC at 60 and 80 cm depth had a similar trend to that of summer. Soil moisture exhibited noticeable seasonal oscillations, and the oscillation in surface soil moisture was greater than that of the deep soil, and the oscillation of surface soil moisture in summer and autumn was greater than that in winter and spring. This was probably due to more frequent rain events and strong root water uptake in summer and autumn than in winter and spring.

4. Discussion

4.1. Response of soil hydrology to thinning

The response of soil moisture content at different depths to rainfall events is a complex process, and is influenced by factors such as rainfall intensity (Schwinning and Sala, 2004; Yaseef et al., 2010), rain event size (Harper et al., 2005; Heisler-White et al., 2008), duration of the dry interval, antecedent soil moisture conditions (Lozano-Parra et al., 2015), and vegetation cover and soil properties (Miller et al., 1983). In this study, large rainfall events with a short dry interval or high intensity rainfalls were necessary to increase VSMC in all stands (Figs. 2 and 3). However,

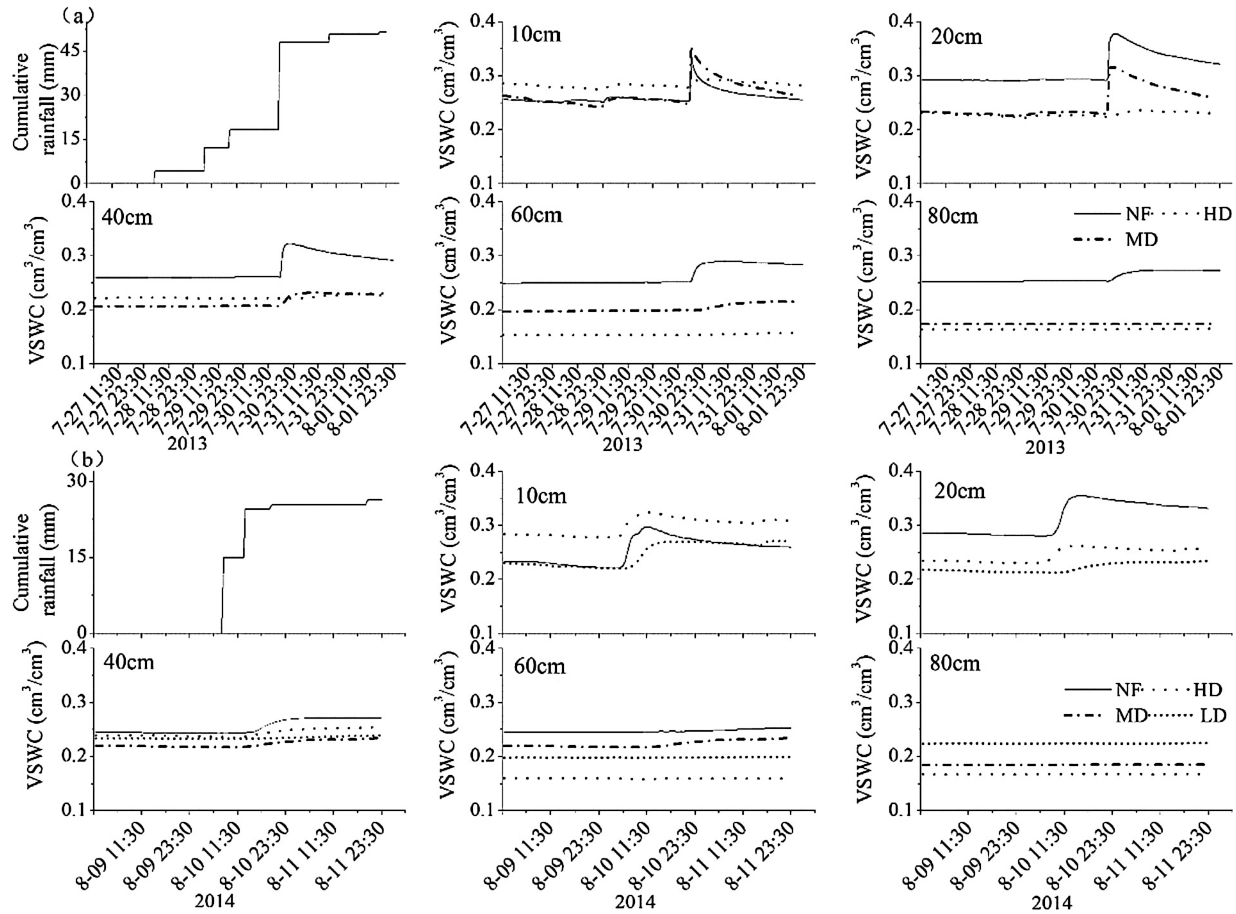

Fig. 3. The response of soil moisture in the NF, LD, HD, MD, and LD to maximum daily rainfall events during the 2013, and 2014 growing seasons.

plantation forests had longer delays of soil wetting and lower VSWC increments than the NF, especially in the deep soil layers. This can be due to the combined effects of factors such as soil-water repellency, interception by canopies, soil properties, and water infiltration capacity, whose influence can vary with time (Doerr and Thomas, 2000; García-Estringana et al., 2013; Sun et al., 2015). We also found that the depth of soil moisture recharge tended to increase with the increase in rainfall amount and intensity, and that moderate-intensity thinning facilitates recharge of the deep soil water (Figs. 2b and 3b). Thinning can lead to a sparse canopy, and increase throughfall, but it can increase surface soil bulk density and decrease soil water infiltration. Due to soil compaction and a decrease in organic matter, soil bulk density had been generally observed to increase following thinning (Carter et al., 2006; Tarpey et al., 2008; Wall, 2012). We found in this study that thinning resulted in a significant increase in soil bulk density in the 0–30 cm soil layers, confirming the results of previous research. In addition, the increase in soil bulk density and decrease in SOC would reduce water holding capacity in soil, which would impede an increase in soil water content. Therefore, the moderate intensity thinning facilitated recharge of the deep soil water.

With the small rainfall events before an extreme precipitation event, large rainfall amounts were more likely to trigger soil water increases in deeper soils in all stands (Fig. 3). Moreover, successive rainfall events enable a faster wetting of canopies, a higher degree of saturation of canopy water storage, and longer periods of throughfall (Crokford and Richardson, 2000; Lozano-Parra et al., 2015). Further, in wet conditions, evaporation is limited by energy availability; the litter layer and high organic contents create forest soils with high macro-porosity, low bulk density, and highly saturated hydraulic conductivities and infiltration rates (Neary et al., 2009). According to previous studies in the Qilian Mountains, soils with low bulk density usually have a high porosity (Cheng et al., 2007; Sun et al., 2015), which is conducive to percolation of moisture into the soil. However, most of the time the wetting processes were slow below trees due to the damping effect of their canopies. Lozano-Parra et al. (2015) found that during dry and semi-dry initial conditions, only rainfall events in excess of 6 mm triggered soil moisture increases below tree canopy, whereas in grassland, only 2 mm of rain was necessary for the soil moisture response. It is important to note that a large number of rain events never caused soil water increases below tree cover under dry and semi-dry initial states, and this was due low rain amounts of <5 mm registered for more than half of all rainy days during the growing season (Fig. 1).

This highlights the role of canopy interception under such conditions. The gross interception loss by tree canopies increases with increasing rainfall, whilst relative interception loss by trees decreases as the rainfall amount increases (Crokford and Richardson, 2000). Many authors have also observed temporal patterns; for example Cantón et al. (2004) reported that rainfall events of <3 mm may or may not have an impact on wetting processes depending on antecedent soil moisture states in a semiarid south-eastern part of Spain. Similar results were observed by Lozano-Parra et al. (2015) in another study in the Mediterranean region; there, under humid conditions, even small rainfall events (<3 mm) produced a soil hydrological response in both forests and grasslands, indicating that rain was not completely intercepted. However, under drier conditions greater amounts or intensities are necessary for rainwater to reach deep soil. Under drier

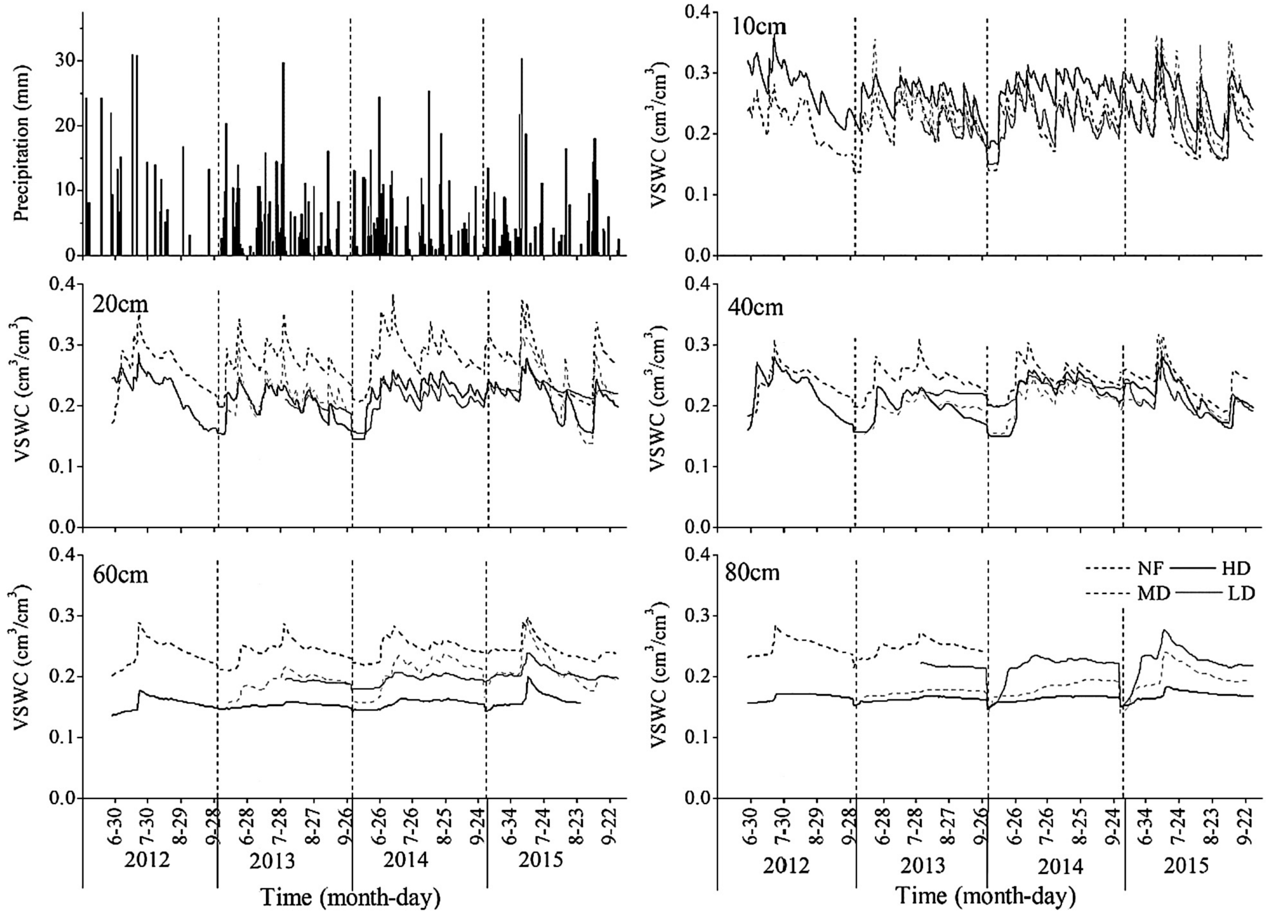

Fig. 4. Daily rainfall and soil moisture dynamics in the NF, HD, MD, and LD during the 2012–2015 growing seasons.

conditions, rainfall events are usually discontinuous, and the evaporative demand during dry gaps is stronger. Further, soil water repellency becomes more important, decreasing gradually as soil becomes wet (Doerr and Thomas, 2000; Schnabel et al., 2013). Therefore, the soil hydrological response may temporarily be modified by thinning, and the role of thinning on rainwater amount reaching soil layers at depth may depend on antecedent soil moisture conditions.

The results obtained in this study are important for predicting changes in precipitation patterns within the global climate change framework. In recent years, many studies highlighted a significant decrease in annual precipitation and in rain days, an increase in annual and seasonal variability, and increased frequency and intensity of dry periods together with an increase in air temperature (Philandras et al., 2011; Trenberth, 2011; IPCC, 2013). These conditions could influence the amount of water reaching the soil, with subsequent impact on the water-sensitive ecosystems (Lozano-Parra et al., 2015). Therefore, a climate change in semiarid regions, as predicted by IPCC (2013), could affect precipitation and temperature regimes, enhancing dry spells and evaporative demand, causing an increase in the interception capacity of vegetation, and consequently affecting ecological processes. Similarly, the frequency and intensity of heavy precipitation events has increased during the growing season (Easterling et al., 2000; Heisler-White et al., 2008; Alpert et al., 2002; IPCC, 2013; Wang et al., 2013); this may lead to an increase in runoff and soil erosion, and a decrease in soil moisture (Cerdá et al., 1998). However, in the western parts of China, the annual total precipitation tended to increase (Wu et al., 2015). Further, rainfall events with the same total rainfall but a higher rainfall intensity increased water infiltration, and surface runoff was not observed in the area (He et al., 2012). Therefore, these results indicate that high rainfall amounts or intensities may be necessary to produce an increase in VSWC in deep soil, and to play a key role in determining SWS in artificial (especially vegetation with high density) and natural forest ecosystems in the Qilian Mountains.

4.2. Response of soil moisture dynamics to thinning

Vegetation impacts on soil moisture dynamics include effects on precipitation due to interception and stemflow (He et al., 2014; Zhang et al., 2016), soil surface temperature due to plant shading (Breshears et al., 1998), soil moisture availability due to plant root water extraction (Scott et al., 2000), soil infiltration capacity due to vegetation patches and root channels (Wilcox et al., 2003), contributions of plants to evapotranspiration (Chang et al., 2014), and deep vadose zone percolation (Seyfried et al., 2005). Since plants play a fundamental role in controlling surface energy and water balance (Gutiérrez-Jurado et al., 2006), different thinning intensities can lead to significant variations in eco-hydrological dynamics. In the present study, thinning significantly changed soil hydrological response and soil moisture dynamics; this may be due to the combined effects of the above factors, and in that, our findings partially confirmed the results of previous studies.

In semi-arid areas, surface soil moisture is more prone to be affected by rainfall, vegetation transpiration, and soil evaporation than in wetter environments (Teuling and Troch, 2005; Seneviratne et al., 2010). Relatively low surface soil moisture is expected due to high evapotranspiration in these regions. How-

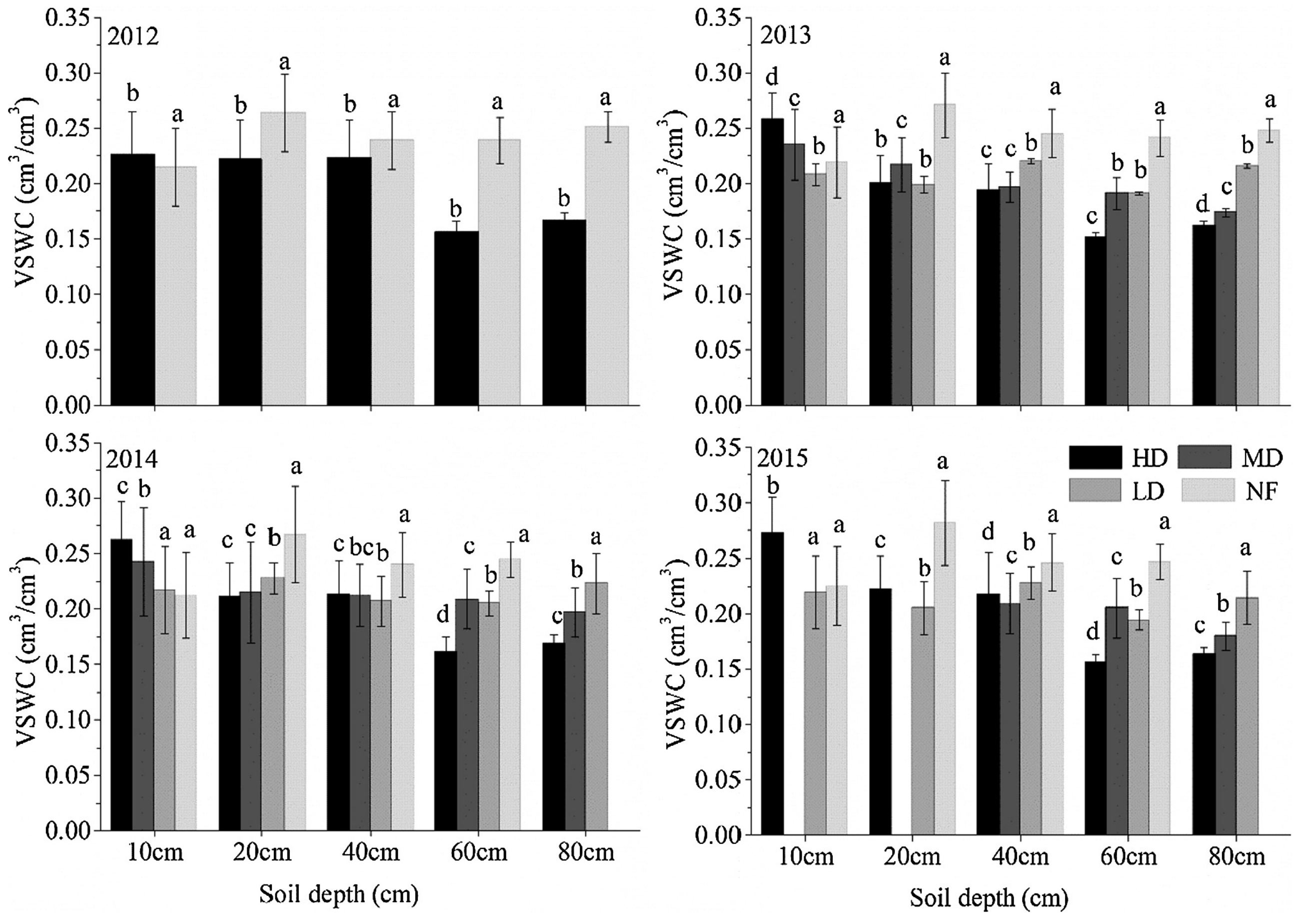

Fig. 5. Vertical changes in soil moisture in the NF, HD, MD, and LD during the 2012–2015 growing seasons. Vertical bars represent 95% confidence limits, the alpha value is 2.5% at each side of the bar. Different lower-case letters above the bars indicate significant differences at $P < 0.05$.

Table 3
Mean soil moisture content in NF, HD, MD, and LD at different depths during the 2012–2015 growing seasons. Values (±SE) followed by different lower-case letters within rows are significantly different at $P < 0.05$.

Year	Soil depth (cm)	HD	MD	LD	NF
2012	10	0.227 ± 0.038	–	–	0.215 ± 0.035
	20	0.222 ± 0.035	–	–	0.264 ± 0.035
	40	0.223 ± 0.034	–	–	0.239 ± 0.026
	60	0.156 ± 0.010	–	–	0.239 ± 0.021
	80	0.167 ± 0.006	–	–	0.251 ± 0.014
	0–80	0.199 ± 0.025	–	–	0.242 ± 0.026
2013	10	0.258 ± 0.024d	0.235 ± 0.032c	0.208 ± 0.017b	0.219 ± 0.032a
	20	0.201 ± 0.025b	0.217 ± 0.024c	0.199 ± 0.007b	0.271 ± 0.029a
	40	0.195 ± 0.023c	0.197 ± 0.014c	0.220 ± 0.002 b	0.245 ± 0.022a
	60	0.152 ± 0.003c	0.191 ± 0.014b	0.191 ± 0.002 b	0.241 ± 0.016a
	80	0.163 ± 0.003d	0.174 ± 0.004c	0.216 ± 0.002b	0.248 ± 0.011a
	0–80	0.194 ± 0.016c	0.203 ± 0.018b	0.207 ± 0.005b	0.245 ± 0.022a
2014	10	0.273 ± 0.032b	–	0.219 ± 0.033a	0.225 ± 0.036a
	20	0.222 ± 0.030c	–	0.205 ± 0.024b	0.282 ± 0.038 a
	40	0.218 ± 0.037d	0.209 ± 0.027c	0.228 ± 0.015b	0.246 ± 0.026 a
	60	0.156 ± 0.007d	0.205 ± 0.027c	0.194 ± 0.009b	0.247 ± 0.016 a
	80	0.164 ± 0.005c	0.180 ± 0.013 b	0.214 ± 0.024a	–
	0–80	0.207 ± 0.022	–	0.212 ± 0.021	–
2015	10	0.263 ± 0.034a	0.243 ± 0.049b	0.217 ± 0.039a	0.212 ± 0.039a
	20	0.212 ± 0.030a	0.215 ± 0.046b	0.228 ± 0.014b	0.267 ± 0.044a
	40	0.214 ± 0.030c	0.212 ± 0.028bc	0.207 ± 0.023b	0.240 ± 0.029a
	60	0.162 ± 0.013d	0.209 ± 0.027c	0.205 ± 0.011 b	0.245 ± 0.016a
	80	0.169 ± 0.008c	0.197 ± 0.022 b	0.223 ± 0.027a	_
	0–80	0.204 ± 0.023 b	0.215 ± 0.034a	0.216 ± 0.023a	_
2012–2015	Average (0–80)	0.201 ± 0.021c	0.209 ± 0.026b	0.212 ± 0.016b	0.243 ± 0.024a

Table 4
Soil water storage (SWS) at soil depth of 0–80 cm in NF, HD, MD, and LD during the 2012–2015 growing seasons. Values (±SE) followed by different lower-case letters within rows are significantly different at $P < 0.05$.

Year	Soil depth (cm)	HD	MD	LD	NF
2012	0–80	158.99 ± 14.27	–	–	193.69 ± 16.55
2013	0–80	148.12 ± 9.07a	157.56 ± 8.64b	166.06 ± 3.13c	195.68 ± 14.15d
2014	0–80	157.22 ± 14.47	–	169.79 ± 14.11	–
2015	0–80	156.55 ± 12.52a	172.84 ± 21.18b	171.35 ± 13.09b	–
2012–2015	Average (0 –8 0)	156.55 ± 12.58a	165.20 ± 14.91b	169.07 ± 10.11b	194.69 ± 15.35c

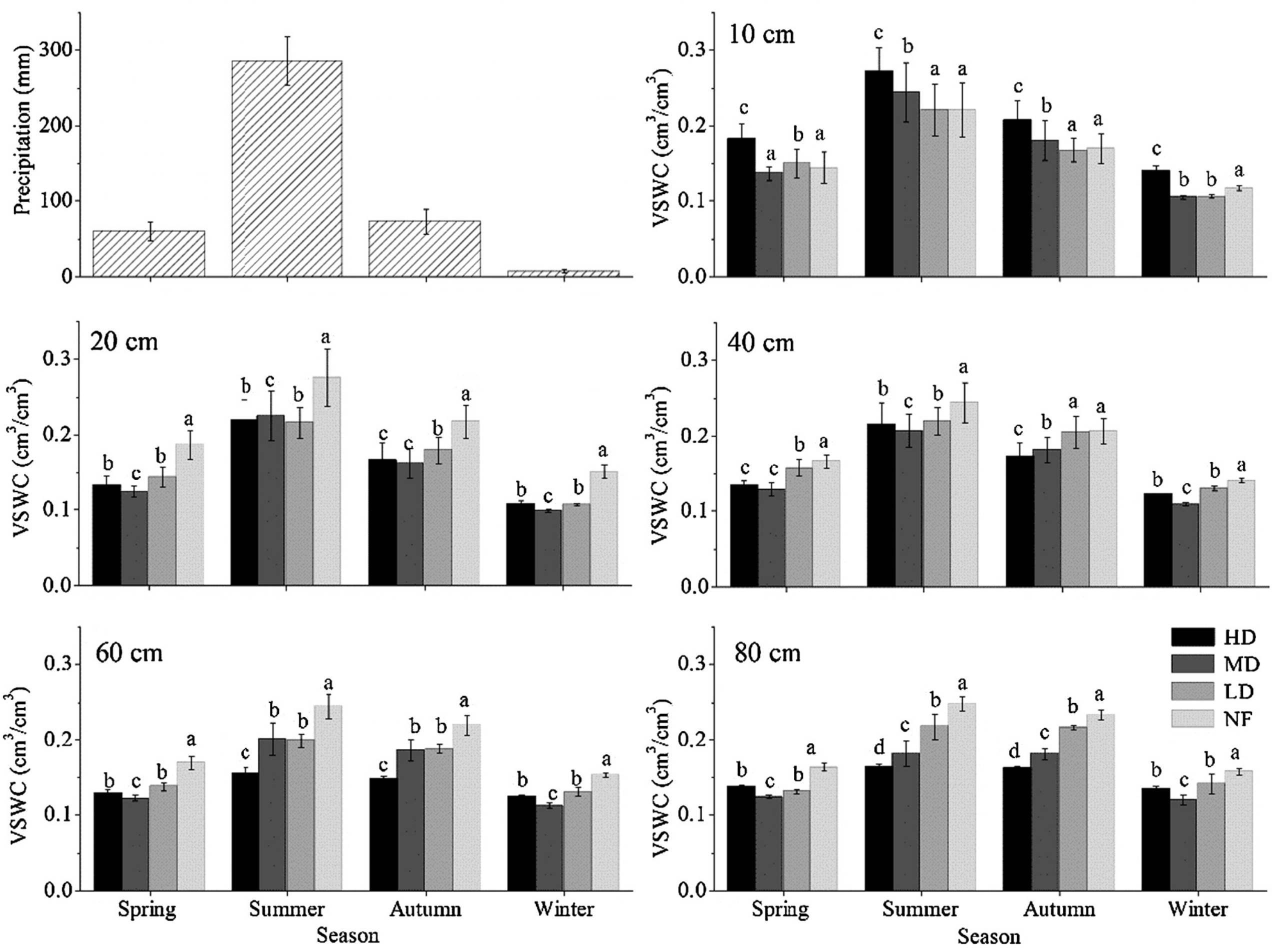

Fig. 6. Seasonal dynamics of soil moisture in NF, HD, MD, and LD during 2012–2015. Vertical bars represent 95% confidence limits, the alpha value is 2.5% at each side of the bar. Different lower-case letters above the bars indicate significant differences at $P < 0.05$.

ever, the HD had the highest surface VSWC of all stands. This was somewhat contradictory to the findings in other study areas (Mishra and Singh, 2010; Yang et al., 2014). Although HD had relatively high canopy interception due to high leaf area indices, the effect of plant shading can decrease radiation levels and surface soil evaporation. In addition, the understory vegetation in HD is mainly composed of mosses (Table 1), known for their excellent water retention (Michel et al., 2012). Further, we also found that surface VSWC tended to decrease with an increase in thinning intensity (Table 3). This was because thinning created a sparser canopy, and the increased radiation levels may enhance soil evaporation and promote a fast growth of secondary or understory vegetation, both of which can accelerate the depletion of soil moisture (Bhatti et al., 2000; Son et al., 2004). In addition, soil bulk density also tended to increase with increasing thinning intensity, which did not benefit deep infiltration and soil water retention.

Root-zone soil moisture is an important water source for vegetation development (Chen et al., 2008b; Fu et al., 2012). In this study, soil moisture in NF served as the reference to evaluate the effects of thinning on soil water dynamics in plantations stands. Compared with NF, VSWC in plantation forests was relatively low but increased with increased thinning intensities, especially in the deep soil layer (Fig. 4). This was mainly because high density plants consumed excessive amounts of soil moisture stored in the sub-surface layers. Previous studies have shown that relatively large-scale clearings can lead to a higher level of soil water content due to reduced interception and transpiration rates (Schrumpf et al., 2011; Gebhardt et al., 2014). In a New Mexico ponderosa pine forest, Zou et al. (2008) showed that the low-density stands consistently had greater soil water contents than the high-density stands, and the effect of transpiration appeared to be greater than that of interception. In a northern temperate mixed successional forest, He et al. (2013) also found that larger water storage resulted from increased net precipitation and reduced transpiration during growing seasons following a girdling operation; these processes "outcompeted" the presumably enhanced interception and transpiration by understory plants as well as increased soil evaporation. In the present study, we found that thinning significantly improved SWS at 0–80 cm depth, but there were no significant differences between MD and LD, partially confirming the results of the study by Zou et al. (2008) and He et al. (2013). Soil moisture below 40 cm could be affected by plant root systems (February and Higgins, 2010), resulting in the driest zone compared with the upper layers. This may explain the relatively low soil moisture in the sub-surface (∼60 cm) layers; similar results were also reported by other researchers (Weltzin and McPherson, 1997; Yang et al., 2014).

To maintain sustainability in vegetation restoration in arid and semi-arid areas, soil moisture conditions should be evaluated before afforestation (Yang et al., 2014). Therefore, there is an urgent need for better management strategies to avoid the emergence of potential conflicts due to poor understanding of the underlying eco-hydrological processes (Wang et al., 2012). Furthermore, due to the reliance on afforestation in vegetation restoration of arid and semi-arid regions (Cao et al., 2011), soil moisture conditions need to be recognized as a critical issue for vegetation restoration in these areas. In order to sustain the vegetation, the soil moisture in sub-surface soil layers needs to be restored. However, the sub-surface soil moisture is difficult to replenish in areas with low annual rainfall (Chen et al., 2008b; He et al., 2012). In this study, we found that thinning practices can effectively increase soil moisture, especially for the sub-surface soil layers. High planting density is the main cause of severe soil moisture deficit on a long-term temporal scale, but it can be mitigated and slowed down by 20–40% thinning (∼3139 trees ha^{-1}) management. Thus, controlling planting density and following appropriate forest management measures may be considered as an effective strategy to promote sustainability of large-scale vegetation restoration and afforestation projects in the semi-arid Qilian Mountains and other similar regions in the world.

5. Conclusions

The surface VSWC in all stands responded to rainfall events first, while deeper layers exhibited a lag effect. Canopy structures, antecedent soil moisture conditions, and precipitation properties affected soil hydrological response both under different thinning regimes in plantation stands and in the natural forest stand. However, due to the differences in canopy structure and soil properties, VSWC at NF can rapidly increase via infiltration into the deep soil layer, greatly improving the utilization efficiency of precipitation. In addition, thinning can significantly change soil hydrological response, and moderate-intensity thinning is conducive to recharge of the deep soil water.

Although thinning significantly decreased surface (10 cm) VSWC, it increased deep VSWC significantly. These results indicated that soil desiccation was present in the deep soil layer (∼60 cm) at HD, but it could be mitigated and even prevented by 20–40% thinning management. Thinning also significantly improved SWS at the 0–80 cm depth, but there were no significant differences between MD and LD. VSWC exhibited a notable seasonal dynamics, expressed as greater oscillations of VSWC in summer and autumn than in winter and spring.

These results indicated that high rainfall amounts or intensities were necessary to produce VSWC increase and to play a key role in determining SWS in artificial and natural forest ecosystems of the Qilian Mountains. Deep VSWC may increase if precipitation patterns shift to produce larger but less frequent rainfall events during the growing season. This change will benefit growth of the vegetation planted at higher density in this area. A qualitative conclusion from this study is that 20–40% thinning management can increase forest soil wetness and improve soil water infiltration and deep soil recharge, which can potentially lead to a higher utilization efficiency of precipitation and a higher recharge of groundwater systems. Our results have direct implications for forest management and restoration in that they provide eco-hydrological insight into ecosystem functioning and can aid in improving restoration practices involving changing *Picea crassifolia* stand density.

Acknowledgements

We are very grateful to Dr Kathryn Piatek for her comments and editorial assistance and to two anonymous referees for their valuable comments to an earlier version of this manuscript. This work was supported by the National Natural Science Foundation of China (Nos. 41621001, 41522102, and 41601051).

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