

## Hydrological properties of litter layers in mixed forests in Mt. Qinling, China

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The litter layer is an important component of forest ecosystems, although little is known about the differences in litter characteristics and hydrological properties of unmanaged, overgrown broadleaved and coniferous mixed forests in the subtropical and temperate zones. This study was carried out in a naturally generated broadleaved and coniferous mixed forest at the Qinling National Forest Ecosystem Research Station, Shaanxi Province, China. We quantified the litter thickness, mass, and its hydrological properties in evergreen pine (*Pinus tabulaeformis*) stands and deciduous oak (*Quercus aliena* var. *acuteserrata*) stands through *in situ* surveys and laboratory immersion experiments. The thickness of the litter layer for *P. tabulaeformis* averaged  $9.3 \pm 2.8$  cm, and it was not significantly different from that detected in the *Q. aliena* stand ( $8.3 \pm 3.6$  cm). The total mass of the litter layer for *P. tabulaeformis*,  $27.94 \pm 9.81$  Mg ha<sup>-1</sup>, was significantly higher than the total mass of  $16.04 \pm 3.60$  Mg ha<sup>-1</sup> found for *Q. aliena*. The mass of the semi-decomposed, fermented litter (OF) layer was significantly higher than that of the non-decomposed litter (OL) layer, irrespective of species. The rate of water absorption by dry litter was the highest at the onset of the immersion experiment and decreased exponentially with time. The water-holding capacity ( $W_m$ ) and water-interception capacity ( $W_i$ ) of the OF layer were higher than the OL layer for both forest stands. The  $W_m$  and  $W_i$  for the *P. tabulaeformis* stand were higher than those for the *Q. aliena* stand at our study sites. The higher  $W_m$  and  $W_i$  for *P. tabulaeformis* may be more effective in ameliorating the splash impact from high-intensity storms to improve water quality, while relatively lower  $W_m$  and  $W_i$  for *Q. aliena* may be considered favorable for augmenting water yield. Forest resource managers should consider those differences along with the other components of the water budget when making management decisions.

**Keywords:** Water Conservation Forest, Hydrological Properties, Forest Succession

### Introduction

Many natural forests and plantations have become overgrown during the past few decades, and this is a global phenomenon (Llorens et al. 1997, Zou et al. 2008, Kuraji 2012, Sun et al. 2014). The implication of

overgrown forests on water resource management in humid regions has been underappreciated in locations where water scarcity is less pressing compared with semiarid and arid regions (Gallart & Llorens 2003, Gomyo & Kuraji 2016). The litter layer

is an important component of forest ecosystems and its importance is often underestimated in water resource management (Schaap et al. 1997, Levia et al. 2005, Ilek et al. 2015). More recent studies have added evidence of a substantial impact of litter on the water budget in semiarid shrubland and woodland with a substantial litter layer (Dunkerley 2000, Chang et al. 2008, Bulcock & Jewitt 2012, Acharya et al. 2017). However, the litter production dynamics, litter layer structure and hydrological properties of secondary forests in humid forest ecosystems, as well as their relevance in water conservation management have not been widely studied. With the increasing acreage of secondary forests and overgrown plantations in subtropical and temperate forest systems, the quantity and quality of ecosystem services provided by those forest stands deserve further studies.

Forest litter, a sponge layer separating precipitation from mineral soil, mediates rainfall splash impact and reduces, delays or often eliminates overland flow and soil erosion from the forest floor (Gao & Zhou

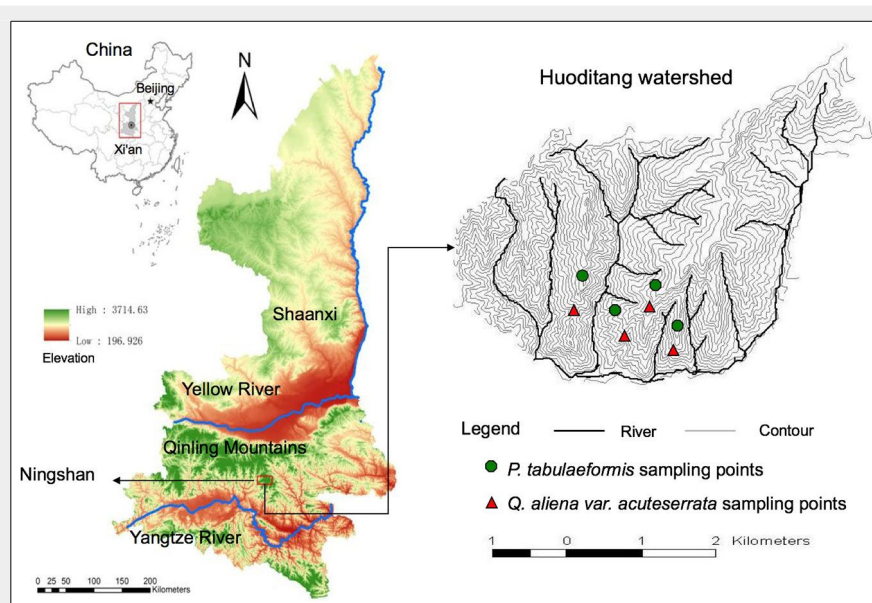
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**Fig. 1** - Geographic location of study site and spatial distribution of sampling points in the Huoditang Watershed, located in the Qinling National Forest Ecosystem Research Station (southern Qinling Mountains, central China, 161 km south of Xian City).

2002, Neris et al. 2013). As a result, the amount of litter and its hydrological properties in a forested catchment could affect not only the water quality but also the water yield of the catchment. A recent study on Japanese red pine (*Pinus densiflora*) and konara oak (*Quercus serrata*) mixed forest in Japan (Gomyo & Kuraji 2016) demonstrated that the litter layer plays an important role in the hydrological cycle of humid ecosystems, and litter removal resulted in the increase of peak flow, particularly during relatively large flood events. However, we know little about the differences in litter characteristics and hydrological properties between broadleaved species and coniferous species in the mixed forests of the subtropical and temperate zones. Such information is particularly useful from the perspective of managing water conservation forests for water yield and water quality (Sato et al. 2004, Komatsu & Rappleye 2017).

The Qinling Mountains are the highest mountain range in central and eastern China, with an east-west length of 1600 km and a north-south width ranging from tens to two-three hundred kilometers. They divide the Yangtze River system to the south and the Yellow River system to the north, and are located in the central and southern part of Shaanxi Province between the Wei River and the Han River. The forest area encompasses gullies, ravines, and streams, and contains abundant water resources reaching a total amount of 22.2 billion m<sup>3</sup> (Wen 2011). The southern slope of the Qinling Mountains has a water resource amount of approximately 18.2 billion m<sup>3</sup> and is an important recharge source for the Danjiangkou Reservoir, the headwater source of the central route of China's South to North Water Diversion Project

(SNWDP – Wen 2011). The average annual streamflow into the reservoir was reported to have substantially decreased in past decades (Liu et al. 2012).

The southern slope of the Qinling Mountains is co-dominated by *P. tabulaeformis* and *Quercus aliena* var. *acuteserrata* (*Q. aliena*, hereafter) between 1300 and 1800 m a.s.l. of elevation. A 30-year-old study quantified the litter characteristics of young and middle-aged *P. tabulaeformis* and *Q. aliena* forests (Lei 1984). Currently, most of those forests have become overgrown due to lack of management. A recent study revealed that the streamflow in this region decreased during the same period as a result of the reduced precipitation, though 10-15% of such decrease was attributed to non-climate related causes, including vegetation (Liu et al. 2012). Nonetheless, there have been no studies on the characteristics and hydrological properties of the litter layer of these forests, especially on possible differences between *P. tabulaeformis* and *Q. aliena* (the dominant species in the area) stands in favoring water resource management.

In this study, we quantified the thickness, mass, and hydrological properties of the litter layer in representative *Pinus tabulaeformis* and *Quercus aliena* stands through *in situ* site surveys and laboratory immersion experiments, with the aim of providing data support and theoretical guidance to water resource management and conservation in the Qinling Mountains.

## Materials and methods

### Study site

The study was carried out in the Huoditang Watershed at the Qinling National Forest Ecosystem Research Station at

Ningshan County, Shaanxi Province, China (33° 18' N, 108° 20' E – Fig. 1). The station is located on the southern slope of the Qinling Mountains, falling within the transition zone of the warm-temperate deciduous broadleaved forest region and the subtropical evergreen broadleaved forest region (Pan et al. 2003). The elevation ranges from 800 to 2474 m a.s.l., declining from east to west. The topography is diverse with mainly southwestward slopes ranging from 20° to 50°. The average annual temperature ranges from 8 to 10 °C. The average annual precipitation ranges from 900 to 1200 mm, with rainfall mostly occurring from May to October and snowfall occurring from November to the beginning of April. The average annual evaporation reaches 800 to 950 mm (Chen et al. 2013). The soil at this site belongs to mountain brown soil, and the bedrock mainly consists of granite, gneiss, metamorphic sandstone and schist (Zhang & Liang 2012). The study site is primarily covered by naturally regenerated, secondary forests. Distinct zoning in forest types exists along an elevation gradient, with the deciduous broadleaved forest distributed at the bottom, coniferous and broad-leaved mixed forest in the middle, and subalpine coniferous forest on the top. In this study, we focused on the *P. tabulaeformis* stands and *Q. aliena* stands forming the coniferous and broadleaved mixed forest at the altitudes ranging from 1300 to 1800 m a.s.l. These stands were primarily naturally regenerated after forest harvesting during the 1960s and the 1970s. For the *P. tabulaeformis* stand, the associated tree species were *Pinus armandi*, *Toxicodendron vernicifluum*, *Carya cathayensis* Sarg, and *Sorbus folgneri*. The shrub layer included *Viburnum dilatatum*, *Stachyurus chinensis*, *Rosa omeiensis*, *Lonicera hispida* Pall; and the herbaceous layer contained *Carex lanceolata* and *Stellaria media*. For the *Q. aliena* stand, the associated tree species included *P. tabulaeformis*, *Acer davidii*, *Carpinus cordata*, *Quercus aliena*, *P. armandi*, *Acer maximowiczii*, and *Toxicodendron vernicifluum*; the shrub layer was dominated by *Rosa multiflora*, *Lespedeza bicolor*, *Abelia dielsii*, *Spiraea fritschiana*, *Euonymus alatus*, and *Corylus heterophylla*; and the herbaceous layer included *Thalictrum aquilegifolium*, *Anemone tomentosa*, *Dryopteris chinensis*, and *Carex duriuscula* sp. *stenophylloides*.

### Litter collection

We selected four *P. tabulaeformis* sites and four *Q. aliena* sites that were representative of the overall stand age and growth condition, located in areas away from the road and relatively free of human disturbance. At each site, a section or an entire surface of a slope was selected following the protocol of "Observation Methodology for Long-term Forest Ecosystem Research" of the National Standards of the People's Republic of China (GB/T 33027-2016). The basic site and stand information are pre-

sented in Tab. 1. For each site, upper, middle, and lower positions were selected. Two 0.5 × 0.5 m quadrats were randomly selected for each slope position for litter sampling. Intact litter layers were collected and the un-decomposed litter (OL layer) and semi-decomposed litter (OF layer) were packed separately into plastic litter bags following the method described in the aforementioned protocol. A total of 96 litter bags (2 species × 4 sites × 3 slope positions × 2 random quadrats × 2 litter layers) were collected. Eight points around each quadrat were randomly selected to measure the average thickness of both OL and OF layers representing that quadrat. Litter bags were sealed and brought back to the laboratory to determine the fresh mass. After fresh mass determination, litter was left to air dry in the lab. Dry mass was determined by drying the air-dry samples in an oven at 85 °C for 12 hours. Collection of litter samples was conducted after all deciduous trees dropped their leaves in November and December of 2013.

#### Laboratory analyses

One sub-sample from each air-dried litter bag was used to compare the litter composition by separating the litter into leaves, needles, branches, cones and herbaceous components for both *P. tabulaeformis* and *Q. aliena* stands. Then, one sub-sample from the air-dried litter bags for each site and slope position ( $n = 12$  per species and litter horizon) was packed into porous nylon bags of known mass and weighed to calculate the corresponding gross dry litter mass ( $m_0$ ) of each sample. The nylon bags were immersed in a water bath for a pre-determined time and then taken out at fixed time intervals and re-weighed to determine the gross wet mass of litter ( $m_i$ ) after full drainage. The water-holding ratio of litter ( $R_i$ , kg kg<sup>-1</sup>) was calculated as the ratio between the total water held in the litter tissue and the dry litter mass using the following formula (eqn. 1):

$$R_i = \frac{(m_i - m_0)}{m_0} \quad (1)$$

where  $R_i$  is the water-holding capacity of litter at the immersion time  $i$  ( $i = 0.5, 1, 2, 4, 6, 8, 10, 12$  and 24 h),  $m_0$  is the dry litter mass and  $m_i$  is the litter mass at the immersion time  $i$  after free drainage.

The litter water-holding capacity ( $R_m$ ) was defined as the highest ratio achieved when the increase of wet mass of litter was negligible with increased immersion time. In this study, the water-holding ratio rarely increased after litter was immersed in water for 24 h, thus  $R_m$  was numerically equivalent to the  $R_{24}$ .

The total water retention capacity of the litter layer ( $W_m$ , Mg ha<sup>-1</sup>) in a given stand was calculated on the unit area basis using the following formula (eqn. 2):

$$W_m = M \cdot R_m \quad (2)$$

Tab. 1 - Basic characteristics of the sampling sites.

Characteristics	Variable	Vegetation type	
		<i>P. tabulaeformis</i>	<i>Q. aliena</i> var. <i>acuteserrata</i>
Topography	Elevation (m)	1542-1774	1423-1752
	Slope aspect	S, SW	S, SW
	Slope (°)	25-35	32-40
Stands characteristics	Height (m)	23.35 ± 3.04	17.33 ± 1.82
	DBH (cm)	23.62 ± 1.94	25.36 ± 2.30
	Age (yrs)	51-65	51-65
	Canopy density (%)	0.85-0.90	0.80-0.85

where  $M$  is the unit litter mass (Mg ha<sup>-1</sup>).

Assuming the water-holding ratio of litter under ambient conditions is  $R_0$ , the maximum water interception capacity of litter ( $W_i$ , Mg ha<sup>-1</sup>) was calculated as (eqn. 3):

$$R_0 = \frac{(m_i - m_0)}{m_0} \quad (3)$$

where  $R_0$  is the water-holding capacity of the litter under ambient conditions,  $m_i$  is the fresh litter mass and  $m_0$  is the dry litter mass (eqn. 4):

$$W_i = (R_m - R_0) \cdot M \quad (4)$$

#### Data analysis and statistics

We treated tree species (*P. tabulaeformis* and *Q. aliena*) and the litter layers (OL and OF) as fixed factors, the site (four representatives for each species) as a random factor, and the slope position (lower, middle and upper) was nested under each site. Linear mixed-effects models were fitted to explore the effects of these factors and their interactions on the litter thickness and mass of the OL layer and OF layer using the “lmerTest” package in R (version 3.4.2). We also fitted models with the total thickness and total mass of the OL layer and the OF layer combined. To check the

model assumptions, we applied the normality test as well as the test of equal variance of the residuals for each model. A logarithm transformation was applied to the total thickness of litter since the original data failed the normality test. For the hydrological properties determined in the laboratory, a Student's t-test ( $\alpha=0.05$ ) was performed.

#### Results

##### Litter composition, thickness and mass

The thickness differed significantly between the OL layer and the OF layer ( $p = 0.001$ ) and this difference depended on the tree species ( $p < 0.001$ ). There was a significant difference in litter mass between tree species and litter layer ( $p < 0.001$ ). The total thickness of both OL and OF layers was not significantly different between tree species ( $p = 0.3178$ ), but different tree species did significantly differ in total mass of either OL and OF layers ( $p < 0.001$  – Tab. 2). The composition of the litter layer and the defoliation period of *P. tabulaeformis* and *Q. aliena* are presented in Tab. 3. The collected litter is mainly composed of leaves or needles. The needles of *P. tabulaeformis* fall both during early spring and later autumn, while the leaves of *Q. aliena* fall mostly during the autumn. The thickness of

Tab. 2 - F-statistics from factorial ANOVA to assess tree species (*P. tabulaeformis* and *Q. aliena* var. *acuteserrata*), litter layer (OL and OF) and slope position (lower, middle and upper) effects on the litter thickness, mass, total litter thickness and total litter mass. (df): degrees of freedom; (SS): sum of squares; (MS): mean square; (ns):  $p > 0.05$ ; (\*):  $p < 0.05$ ; (\*\*):  $p < 0.01$ ; (\*\*\*) :  $p < 0.001$

Variable	Factor	df	SS	MS	F-value	P-value
Litter thickness	Species	1, 42	2.8	2.8	0.367	0.3671 <sup>ns</sup>
	Litter layer	1, 42	41.44	41.44	0.001	0.001 <sup>**</sup>
	Slope position	2, 42	0.34	0.34	0.951	0.9512 <sup>ns</sup>
	Species × Litter layer	1, 42	85.86	85.86	0	<0.0001 <sup>***</sup>
Litter mass	Species	1, 39	9.24	9.24	36.64	<0.0001 <sup>***</sup>
	Litter layer	1, 39	3.44	3.44	13.63	0.0006 <sup>***</sup>
	Slope position	2, 7.7	1.14	0.57	2.27	0.1669 <sup>ns</sup>
	Species × Litter layer	1, 39	0.47	0.47	1.89	0.1767 <sup>ns</sup>
Log (Total litter thickness)	Species	1, 20	0.164	0.164	1.04	0.3178 <sup>ns</sup>
	Slope position	2, 20	0.013	0.006	0.04	0.9591 <sup>ns</sup>
Total mass	Species	1, 17	851.09	851.09	27.32	<0.0001 <sup>***</sup>
	Slope position	2, 6.43	119.91	59.96	1.92	0.221 <sup>ns</sup>

**Tab. 3** - Composition of the litter layer and defoliation period of *P. tabulaeformis* and *Q. aliena* var. *acuteserrata*.

Characteristics	Vegetation type	
	<i>P. tabulaeformis</i>	<i>Q. aliena</i> var. <i>acuteserrata</i>
Woody litter	Leaf (%)	86.1
	Branch (%)	10.8
	Cone, seed scale, others (%)	2.7
Shrub and herb litter (%)	0.4	0.5
Defoliation period	Mar. to Apr., Nov. to Dec.	Sep. to Nov.

(Fig. 3a). This relationship was similar between the two types of litter. The water-holding ratio was relatively higher for OF compared to the OL at the same immersion time. However, the water-holding ratio of the OF of *Q. aliena* did not increase substantially with an increase in the time of water immersion (Fig. 3b) and was mostly lower than the OF of *P. tabulaeformis*.

#### Litter water-absorption rate

The water-absorption rates of undecomposed and semi-decomposed litter layer were highest at the beginning of the experiment and declined quickly in the first 4 hours. The rate slowed down during the time interval of 4-8 h, and was nearly unchanged after 8 h (Fig. 4). The water-absorption rate of the OL was 2.99 kg kg<sup>-1</sup> h<sup>-1</sup> and 2.89 kg kg<sup>-1</sup> h<sup>-1</sup> for *P. tabulaeformis* and *Q. aliena*, respectively, at the first 0.5 h (Fig. 4a). The water-absorption rate of the OF was 5.80 kg kg<sup>-1</sup> h<sup>-1</sup> and 6.39 kg kg<sup>-1</sup> h<sup>-1</sup> for *P. tabulaeformis* and *Q. aliena*, respectively (Fig. 4b). There were no observable differences in water-absorption rates between *P. tabulaeformis* and *Q. aliena* at the same time of water immersion.

#### $R_m$ , $W_m$ and $W_i$

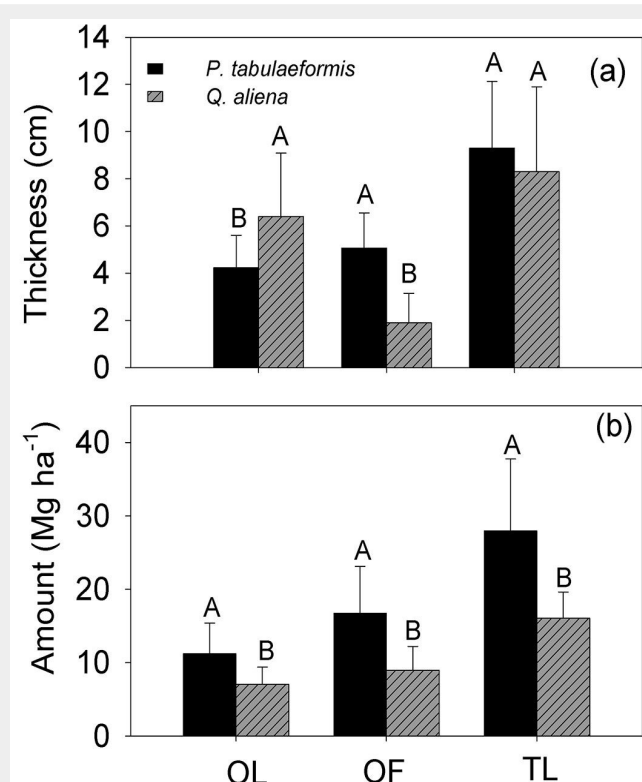
The litter water-holding capacity ( $R_m$ ) of the OL was 199.45 ± 22.83% for *P. tabulae-*

the OF of *P. tabulaeformis* stand was 5.1 ± 1.5 cm (mean ± standard deviation), slightly larger than the 4.2 ± 1.4 cm thickness of its OL. The OF of *Q. aliena* was 1.9 ± 1.2 cm, significantly lower than the 6.4 ± 2.7 cm thickness of its OL ( $p = 0.001$ ). The combined depth of the OF and OL (total litter mass, TLL) of *P. tabulaeformis* was 9.3 ± 2.8 cm, not significantly different from the 8.3 ± 3.6 cm depth of *Q. aliena* (Fig. 2a). The mass of the *P. tabulaeformis* litter layer was 27.94 ± 9.81 Mg ha<sup>-1</sup>, significantly higher than the 16.04 ± 3.60 Mg ha<sup>-1</sup> mass of the *Q. aliena* litter layer ( $p = 0.001$  - Fig. 2b). The mass of the OF layer was higher than the mass of the OL layer in both stand

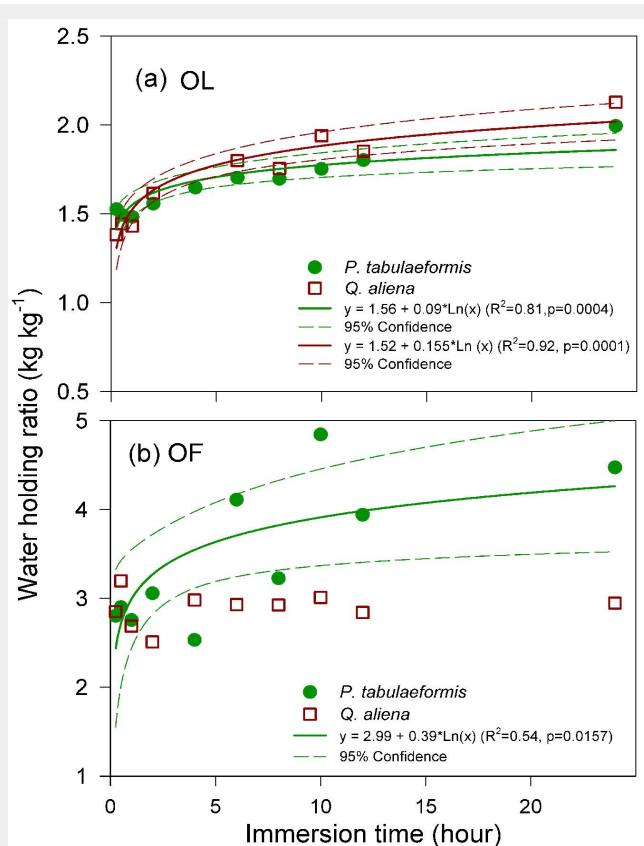
types (Fig. 2b). The mass of the OF layer was 16.74 ± 6.36 Mg ha<sup>-1</sup> for *P. tabulaeformis*, accounting for 59.85 ± 8.46% of the total litter mass, and 8.98 ± 3.23 Mg ha<sup>-1</sup> for *Q. aliena*, accounting for 55.49 ± 14.43% of the total litter mass.

#### Water-holding capacity of litter

After one hour of water immersion, the water-holding ratio of OL and OF reached 74.30% and 61.61% of their holding capacity in *P. tabulaeformis*, respectively, while it was 67.26% and 91.26% in *Q. aliena*, respectively. The relationship between the water-holding ratio of OL and the time immersion in the water was fitted to a logistic model

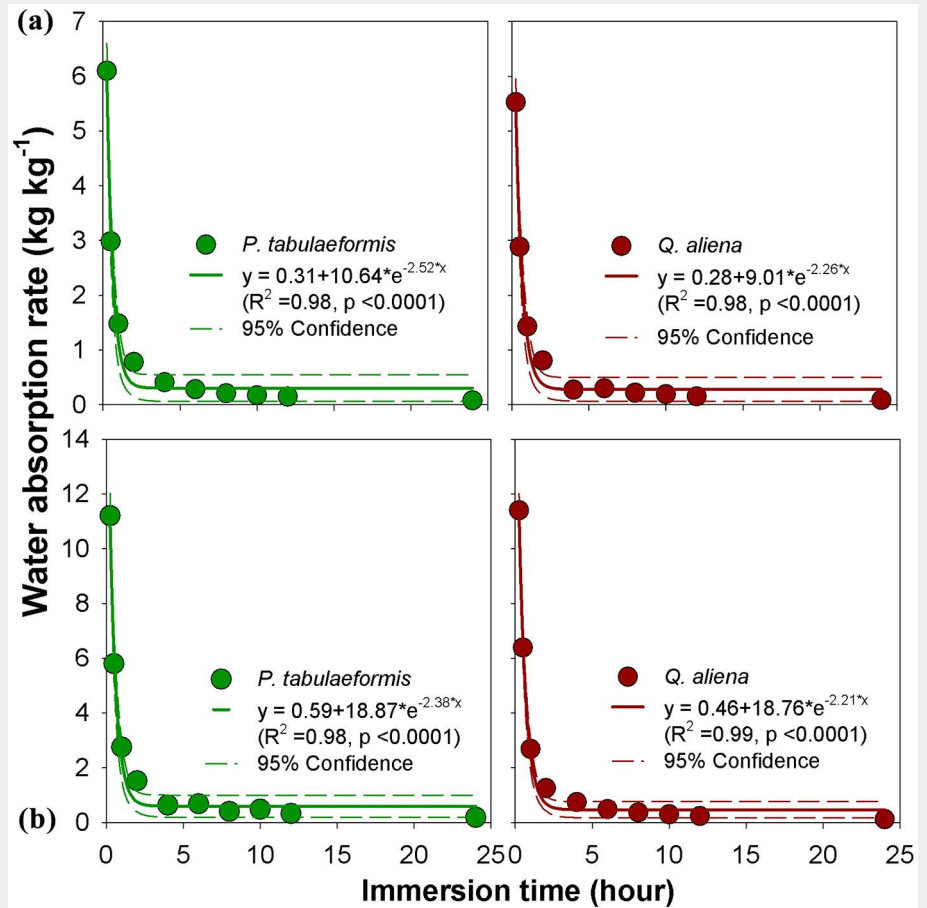


**Fig. 2** - Comparison of the mean thickness and masses of the non-decomposed litter layer (OL), the semi-decomposed litter layer (OF), and the total litter (TL) of *P. tabulaeformis* and *Q. aliena* var. *acuteserrata*. The vertical bar represent the standard error ( $n = 12$ ). For each category, different capital letters indicate a significant difference in the mean value between the two species.



**Fig. 3** - Relationships between the water-holding ratio and the immersion time of (a) non-decomposed litter (OL) and (b) semi-decomposed litter (OF) collected from *P. tabulaeformis* stands and *Q. aliena* var. *acuteserrata* stands. Each point is the average value of 12 replicates.

**Fig. 4** - Litter water-absorption rate of (a) non-decomposed litter (OL) and (b) semi-decomposed litter (OF) of *P. tabulaeformis* and *Q. aliena* var. *acuteserrata*. Each point is the average value of 12 replicates.



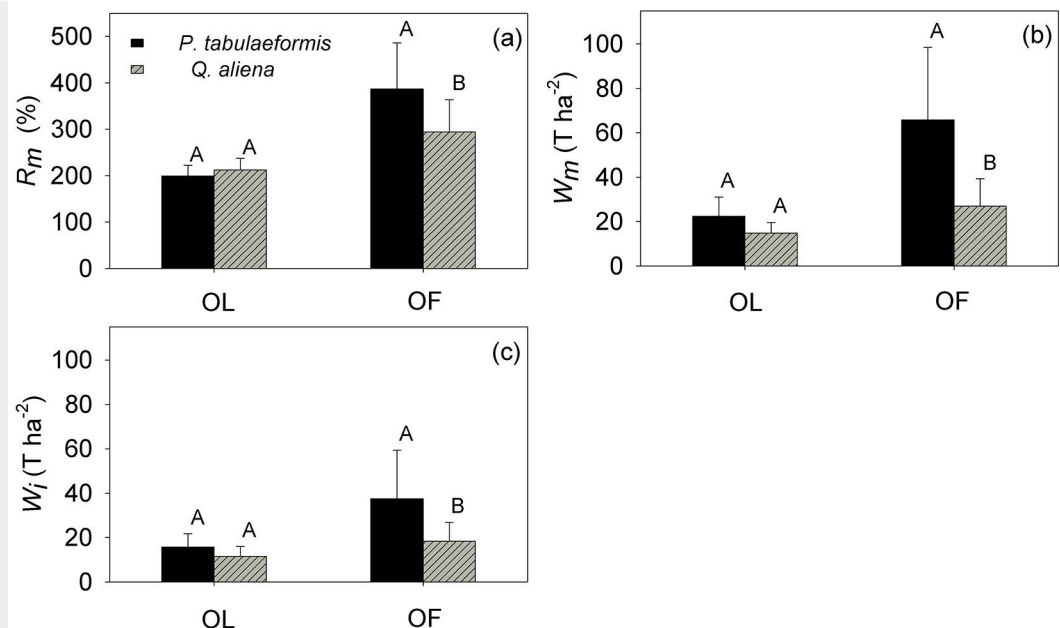
*formis*, not significantly different from the value observed for *Q. aliena* ( $212.76 \pm 24.64\%$ ). The  $R_m$  of the OF for *P. tabulaeformis* was  $386.80 \pm 99.33\%$ , significantly higher than  $294.53 \pm 69.21\%$  for *Q. aliena* ( $p < 0.05$  – Fig. 5a).

The total water retention capacity ( $W_m$ ) of the OL for *P. tabulaeformis* was  $22.35 \pm 8.68 \text{ Mg ha}^{-1}$ , which was not significantly

different from  $14.82 \pm 4.78 \text{ Mg ha}^{-1}$  for *Q. aliena*. The  $W_m$  of the OF was  $65.87 \pm 32.66 \text{ Mg ha}^{-1}$  for *P. tabulaeformis*, significantly higher than  $26.91 \pm 12.38 \text{ Mg ha}^{-1}$  observed for *Q. aliena* (Fig. 5b). The  $W_m$  of the entire litter layer for *P. tabulaeformis* was  $88.22 \pm 38.24 \text{ Mg ha}^{-1}$ , which was nearly two times the value of  $41.74 \pm 12.63 \text{ Mg ha}^{-1}$   $W_m$  for *Q. aliena* (Fig. 5b).

The maximum water interception capacity ( $W_i$ ) of the OL was  $15.82 \pm 5.96 \text{ Mg ha}^{-1}$  for *P. tabulaeformis*, which was not significantly different from  $11.52 \pm 4.40 \text{ Mg ha}^{-1}$  for *Q. aliena*. The  $W_i$  of the OF was  $37.53 \pm 21.86 \text{ Mg ha}^{-1}$  for *P. tabulaeformis*, which was significantly higher than the  $W_i$  detected for the OF layer in *Q. aliena* ( $18.39 \pm 8.50 \text{ Mg ha}^{-1}$  – Fig. 5c).

**Fig. 5** - (a) Maximum water-holding capacity ( $R_m$ , %), (b) maximum water retention capacity ( $W_m$ ,  $\text{T ha}^{-2}$ ), and (c) maximum water interception capacity ( $W_i$ ,  $\text{T ha}^{-2}$ ) of the non-decomposed litter layer (OL) and the semi-decomposed litter layer (OF) of *P. tabulaeformis* and *Q. aliena* var. *acuteserrata*. The vertical bar represents the standard error ( $n = 12$ ). For each category, different capital letters indicate significant differences in the mean value between the two species.



## Discussion

*P. tabulaeformis* is an evergreen pine tree and its needles last for three to four years (Mu et al. 2015). The litter fall is concentrated between March and April and between November and December, with the litter fall from these two periods accounting for 50% of the annual litter fall. The needles account for more than 85% of the total litter. Contrastingly, the litter fall of the broadleaved *Q. aliena* is concentrated between September and November, with few leaves, dead branches and cones falling at other times (He et al. 2011). In this study, the *P. tabulaeformis* stands were at the near-mature stage and dead branches, cones, seeds, and flakes made up approximately 3% of the whole litter. These litter components are slower to decompose as compared with needles and leaves, and result in the accumulation of a thick litter layer and a relatively large litter mass (Shi et al. 2009, He et al. 2012). We found that the percentage of undergrowth shrub and herbaceous litter was relatively small, only 0.4% and 0.5% in *P. tabulaeformis* and *Q. aliena* stands, respectively (Tab. 3). The litter of *Q. aliena* contains a high carbohydrate content and low Klason lignin content, and decomposes more easily than that of *P. tabulaeformis*. The leaf litter decomposition half-life is 1.26 years for *Q. aliena*, much shorter than the 2.28 years reported for *P. tabulaeformis* (He et al. 2011, Han et al. 2012).

The litter layer is reported to substantially reduce the evaporation from mineral soil (Liu et al. 2011, Wang et al. 2013). Therefore, a thick litter layer or the conservation of the litter layer may favor moisture retention in shallow soil. On the other hand, the precipitation intercepted by the litter layer will mostly evaporate back into the atmosphere, and this loss can be substantial in a hot and dry climate (Acharya et al. 2017). The net effect of litter on forest surface water flux deserves further study in the studied climate conditions.

Gong et al. (2006) reported a rapid rise in the water content and a fast increase in the litter water-holding ratio at the onset of the water-immersion experiment in the laboratory. This is related to the low matrix water potential associated with drier litter. Our study showed that the absorption rate decreases exponentially when the litter becomes moist (Fig. 4). The litter in arid and semiarid ecosystems often has a low moisture content, whereby exhibits a great potential to retain the occurring rainfall. The semi-decomposed litter layer (OF) was able to quickly reach a high water-holding ratio of approximately 3 within an hour, which was higher than the non-decomposed litter layer (OL) at its holding capacity (Wang et al. 2004). This may be explained by the fact that the OF has a higher degree of fragmentation, a larger surface area per mass unit and is more conducive to water entrance (Liu et al. 2005). This characteristic is important in retaining water from high-

intensity rainfall.

In this study, the OL of *P. tabulaeformis* stands showed a lower  $R_m$  than that of *Q. aliena* stands, which is consistent with previous reports (Qi et al. 2011). This difference in hydrological properties is likely attributed to the difference in physical and chemical properties of the needles and leaves, since the non-decomposed needles of *P. tabulaeformis* have thicker cuticles and a higher oil content than the leaves of *Q. aliena* (Gong et al. 2011). Additionally, our results showed that the value of  $R_m$  for non-decomposed coniferous tree species was lower than that observed for broadleaved tree species in general (Zhang et al. 2010). In contrast, the  $R_m$  for the OF of *P. tabulaeformis* was nearly twice as great as the  $R_m$  for the semi-decomposed litter of *Q. aliena*. The OF of *Q. aliena* reaches its water-holding capacity quickly while it takes hours for the OF of *P. tabulaeformis* to reach its holding capacity. Further studies are needed to throw light on the biological and hydrological mechanisms underlying the above evidence, as well as to better understand whether such differences are either species-specific or more general between conifers and broadleaves.

While the  $R_m$  defines the effectiveness of unit mass litter in retaining water, ultimately the water retention capacity of the litter layer ( $W_m$ ) depends on the litter mass (Zhang et al. 2010, Li et al. 2013). Our study showed that the water-retention capacity of *P. tabulaeformis* is nearly two-fold that of *Q. aliena* as a result of greater mass and more effective OF. However, Zhang et al. (2010) reported a smaller water-retention capacity of the semi-decomposed OF layer as compared to the non-decomposed OL layer, and Li et al. (2013) showed a higher water retention capacity in broadleaved than in coniferous forest litter of co-occurring stands in other forest ecosystems. A comprehensive study is needed to systematically investigate litter characteristics and their hydrological properties across different climate regimes and forest ecosystems, also aiming to assess the latent heat transfer, the microclimate for microbes, and the carbon flux from forest litter.

The water interception capacity ( $W_i$ ) of the litter is a hydrological property which sets the upper limit of precipitation loss to the litter layer for any given event. This value varies depending on the antecedent litter water content, which varies substantially under a hot and dry climate (Acharya et al. 2017). A simple conversion of  $W_i$  obtained in this study suggests that the litter layer can theoretically intercept up to 53.35 mm of throughfall in *P. tabulaeformis* stands and up to 29.91 mm in *Q. aliena* stands (Fig. 5c). This provides a substantial capacity to minimize the splash erosion from high-intensity storms. Chen et al. (2008) reported that surface runoff rarely occurs until the rainfall is above 50 mm for the *P. tabulaeformis* forest in the Miyun District of Beijing. There is a little surface

runoff in the forested area of this study; however, it is largely unknown whether  $W_i$  will be reached *in situ* for a given storm. Recent development in the measurement of *in situ* litter water content may provide more realistic estimates of the rainfall interception by the litter (Wang et al. 2013, Acharya et al. 2017). Nevertheless, the  $W_i$  value may give a useful indication of the maximum litter interception and a combination of both approaches may improve our estimation of water flux in the forest ground, which is important not only for the hydrological budget but also for an improved understanding of energy partitioning and microbe-driven carbon flux in forest ecosystems.

The *P. tabulaeformis* and *Q. aliena* mixed forest analyzed in this study is at a late successional stage for this climate zone, and is the result of forest harvesting carried out in the 1960s and the 1970s (Yu et al. 2013). From the perspective of water resource management, our results suggest that *P. tabulaeformis* stands have a dense litter layer suitable to intercept rainfall and buffer storm impact. The increase in litter mass along with the development of an overgrown canopy of *P. tabulaeformis* may be one of the aforementioned non-climate causes and can be partially responsible for the decreasing trend in the streamflow (Liu et al. 2012). *P. tabulaeformis* is an endemic species in northern China and will eventually out-compete *Q. aliena* at the mid-elevations of the Qinling Mountains (Zhang 1989).

The precipitation in the Qinling Mountains area is characterized by uneven seasonal distribution and large annual variation. The majority of rainfall is concentrated from May to October, accounting for more than 85% of the annual precipitation with frequent occurrence of heavy rains, torrential rains, and other extreme weather events. Moreover, the mountainous topographic features of this area are prone to geological disasters, including floods, mudslides and landslides (Chen et al. 2013). From the management perspective, a thick and dense litter layer may favor the delay and decrease in the formation of surface runoff, reducing the occurrence of geological disasters. Strategic removal of some unhealthy *Q. aliena* trees may promote *P. tabulaeformis* growth, thus improving litter layer characteristics. Conversely, in areas with low precipitation, such as the Loess Plateau, the rocky mountain area of North China and other areas, the thin litter layer of forest or savanna dominated by *Q. aliena* may be considered favorable to rainfall infiltration and potential streamflow enhancement. Additionally, the quantity and quality of litter affects the morphology and properties of soils as well as the nutrition of plants and soil heterotrophic organisms (Ilek et al. 2015).

The overgrown secondary forests on the Qinling Mountains are the result of the lack of management in the past, similar to the

vast cypress and red cedar plantations in Japan (Kuraji 2012, Sun et al. 2014). The impact of overgrown plantations on the hydrologic budget and water quality requires further studies to sustain the multiple ecosystem services provided by forests (Sun et al. 2014, Komatsu & Rappleye 2017).

## Conclusions

The overgrowth of the mixed forests in the Qinling Mountains causes uncertainty on their current water-conservation function. We studied the structure and hydrologic properties of the litter layer in stands of the two dominant species, *P. tabulaeformis* and *Q. aliena*, finding significant differences between them. *P. tabulaeformis* stands have a much thicker semi-decomposed layer with a higher water-holding capacity than *Q. aliena* and is likely more effective in reducing overland flow and surface erosion. The selective removal of *Q. aliena* trees in overgrown mixed forests may promote the growth of *P. tabulaeformis* and improve water quality. However, the impact of *Q. aliena* removal on the total evapotranspiration of the forest is unknown. Further studies should aim at directly quantifying the impact of different scenarios of tree removal and their impact on water balance and water yield using an experimental watershed approach.

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