Effect of Substituting Plantation Species for Native Shrubs on the Water-holding Characteristics of the Forest Floor on the Eastern Tibetan Plateau

PANG Xueyong and BAO Weikai *

Key Laboratory of Ecological Restoration, Chengdu Institute of Biology, CAS, Chengdu 610041, China

Abstract: Although the forest floor plays important roles in water-holding and nutrient cycling, there is not enough knowledge of the functional changes of the forest floor resulting from changes in vegetation. To evaluate the effect on the hydrological properties of forest floor by the substitution of plantation species for native coppice, we selected four species substituting plantations and one native coppice (secondary native broad-leaved forest, dominated by Quercus liaotungensis and Corylus heterophylla var. sutchuenensis) (QC) as a comparison forest. The substituting plantations were Cercidiphyllum japonicum (Cj), Pinus tabulaeformis (Pt), Pinus armandi (Pa), Larix kaempferi (Lk). These were established in 1987 with a stocking density of approximately 2500 stem ha \(^{-1}\). Thickness and the amount of floor in coniferous plantations were significantly higher compared to secondary native broad-leaved forest and pure broad-leaved plantation. The maximal water-holding capacity of the floor showed the same trend as thickness and amount of litter. Main contributors to the difference in hydrological characteristics in the plantations were the quantity of forest floor and the maximal water holding capacity per unit weight of the floor. The relationships between water absorption processes, water absorption rate and the immersion time for litter, fitted to logarithmic and exponential regressions, respectively. Water absorption processes differed significantly between the various plantations and different decomposition floor horizons. Water absorption characteristics were influenced by leaf structure in various tree species and the degree of decomposed litter. Our results showed that litter amount in coniferous plantations were significantly higher than in deciduous broad-leaved plantation. This suggests that a large amount of nutrients are held in the litter horizon, delaying return to the soil and utilization by plants. At the same time, maximal water-holding capacity of the forest floor in F [fermentation] and H [hummus] horizons was significantly higher than that in L [fresh litter] horizon. Therefore, improving litter transformation from L horizon to F and H horizons by promoting forest floor environment would be one of the best methods for plantation management.

Key words: forest floor; plantation substitution; water absorption rate; water-holding capacity; ecology restoration; eastern Tibetan Plateau

1 Introduction

The forest floor is an accumulation of dead organic plant matter above mineral soil that influences hydrologic characteristics within forest ecosystems (Clary and Ffolliott 1969; Yoshida and Hijii 2006). As the topmost soil compartment, it plays an important role in the forest ecosystem (Greiffenhagen et al. 2006; Rao and Zhu 2007). It is indispensable to ecosystem stability and ecological function (Xiong et al. 2008). The role that the floor plays in ecosystems was recognized as early as the 1850s and has been documented by a large number of studies worldwide (Sayer 2006). In recent years, numerous studies have shown that the floor contributes to forest ecosystems mainly through nutrient and carbon turnover during decomposition, thus maintaining biogeochemical cycling in ecosystems (Xiong et al. 2008). However, little research has concentrated on the hydrological characteristics of the...
forest floor, which plays important roles in the infiltration of rainwater into the mineral soil, the relationship between litter amount and its water-holding capacity, and the interception of precipitation in the whole forest ecosystem.

Any changes in forest structure, tree species, the degree of litter decomposition or stand density may affect the hydrological function of the forest floor (Wiersum 1983; Richard and Granillo 1985; Liu and Wu 1991; Dabne 1998; Ma and Yang 1994; Wang and Li, 1994; Wang 2000). Large areas of native forest in southwest China, especially subalpine coniferous forest and broadleaved deciduous forest, have been clear-felled since the 1950s to meet the demands for timber, fuel and other forest products (Wang and Wang 2007; Wu 2007; Pang et al. 2011). These extensive areas have almost all been replaced by different tree species plantations (Pang et al. 2004; Wang and Wang 2007). There has been a decline in yield and soil fertility under pure plantations and this is an issue of concern (Wu 2007). Much research has been conducted on the litter characteristics of different forest types in different areas. There has been a considerable advance in knowledge on litter amount, litter dynamic balance, the effects of litter on soil structure and mineral cycle, rain water holding, reducing water evaporation from soil, increasing water infiltration into soil, and the effects on runoff and soil erosion (Chen and Xie 1994; Zhang and Wang 1997; Zhang et al. 2001; Zhu et al. 2001; Cheng et al. 2002; Pang et al. 2005; Wahl et al. 2005; Zhang et al. 2006). However, there is little available information on the influence of forest conversion on the hydrological characteristics of the forest floor where native thicket is replaced by plantation species. We hypothesize that hydrological properties of the forest floor are influenced by different decomposition stages and different tree species. Our aims are (i) to investigate the amount of forest floor and the maximal water holding capacity of the floor for different tree species plantations and (ii) to expound on the relationship of water absorption amount and rate of different floor decomposing stages.

2 Materials and methods

2.1 Study site

This study was conducted at the Maoxian mountain Ecosystem Research Station, Chinese Academy of Sciences in Sichuan, China, located in eastern Tibetan Plateau (31° 37’ N, 103° 54’ E). The climate is mountain temperate with a mean annual precipitation of 900 mm, falling mainly from May to September; October to April is the dry season. The mean annual temperature is 8.9°C with the mean maximum monthly temperature of 18.8°C in July and the mean monthly minimum of −1.1°C in January. Soil is Udic luvisols according to the second edition of Chinese Soil Taxonomy (1995), and results from the weathering of metamorphic rock consisted of phyllite, slate and schist.

Planting of exotic species to replace the native thicket has been carried out in the last 40 years in western China. Our research took place in August 2007 and covered four plantation forests (Pinus tabulaeformis [Pt], Pinus armandi [Pa], Larix kaempferi [Lk], Cercidiphyllum japonicum [Cj]) and one native secondary coppice forest (dominating by Quercus liaotungensis and Corylus heterophylla var. sachuenensis [QC]). Pt, Pa, Lk and Cj plantations are tree species that are commonly selected when restoring or replacing native thicket in western Sichuan. The site had been natural thicket before these plantations were created. These plantations were established with terracing in spring of 1987 after clear-felling part of the native thicket in autumn of 1986. They have not been fertilized. There were similar soil properties between the native secondary coppice forest and the four plantations prior to the establishment of the plantations. Measured litter fall from the overstory of Pt, Pa, Lk, Cj plantations and QC coppice amounts to 4.4, 5.1, 4.8, 3.8 and 4.4 t ha⁻¹ y⁻¹, respectively (Pang et al. unpublished data). Canopy closure of the four plantations was more than 85%. The understory coverage of the sites was less than 10%, especially in the Pa and Pt plantations where it was less than 5%. The understory species were mainly native broad-leaved species, including Quercus aliena var. acuteserrata, Corylus heterophylla var. sachuenensis, Rosa spp., Spiraea spp. Phlanis umbrosa, Voila spp., Anaphalis sinica, Potentilla spp., without any one species being absolutely dominant. The other main characteristics of the forest stands are summarized in Table 1.

### Table 1 The basic information of different forest types in the study area*.

<table>
<thead>
<tr>
<th>Forest types</th>
<th>Elevation (m)</th>
<th>Aspect</th>
<th>Slope</th>
<th>Canopy density</th>
<th>Average tree height (m)</th>
<th>DBH (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CJ</td>
<td>2050</td>
<td>Northwest</td>
<td>14°</td>
<td>0.88</td>
<td>10.2</td>
<td>11.4</td>
</tr>
<tr>
<td>PT</td>
<td>2060</td>
<td>Northwest</td>
<td>10°</td>
<td>0.95</td>
<td>8.4</td>
<td>10.0</td>
</tr>
<tr>
<td>PA</td>
<td>2080</td>
<td>Northwest</td>
<td>7°</td>
<td>0.98</td>
<td>9.8</td>
<td>11.1</td>
</tr>
<tr>
<td>LK</td>
<td>2085</td>
<td>Northwest</td>
<td>17°</td>
<td>0.82</td>
<td>11.3</td>
<td>12.9</td>
</tr>
<tr>
<td>QC</td>
<td>2000</td>
<td>Northwest</td>
<td>25°</td>
<td>0.85</td>
<td>3.0</td>
<td>5.2</td>
</tr>
</tbody>
</table>

* DBH: tree diameter at breast height; PT: Pinus tabulaeformis, PA: Pinus armandi, LK: Larix kaempferi, CJ: Cercidiphyllum japonicum, QC: native coppice (dominating by Quercus liaotungensis and Corylus heterophylla var. sachuenensis).
2.2 Experimental design and sampling

Typical forest types in this area were plotted for our research and included four restoring plantations and one native secondary coppice forest (Table 1). Frame process of different plantations substituting the native thicket is shown in Fig. 1.

Samples of the forest floor of the four plantations and the one native thicket were collected. In each typical forest stand three plots were randomly established with the size of 10 m×20 m in an area of about 0.5 ha. In each plot, three small plots with the size of 50 cm×50 cm along the slope were set as well for litter collection. They were located at the lower, medial and upper sites of the stand. We firstly surveyed the layer thickness. Then before collecting litter, we separated it into different horizons representing different litter decomposition stages (Clary and Ffolliott 1969; Yi et al. 2006). They are (i) the fresh litter layer (L): Leaves remained fresh, not decomposed and undamaged; (ii) the fermentation layer (F): The litter appeared half decomposed (mostly with mildew). Most leaf blades were stuck together, the tissue structures of the plant residues were discernible to the naked eye, and no inorganic soil was mixed in; and (iii) the humus layer (H): The litter was completely decomposed. Structural features of the original plants were indiscernible to the naked eye and a small amount of inorganic soil was mixed in. We then put them into different plastic bags and brought them back to the laboratory and oven-dried them at 80˚C, removing all moisture. They were then weighed.

2.3 Analysis of hydrological characteristics of forest floor

Sub-samples for each collected floor sample were put into nylon mesh bags (mesh size ø=0.5 mm) and soaked in water to measure water-holding characteristics. They were taken out of the water for weighing after 1, 2, 4, 8, 12 and 24 h. Before weighing, samples were allowed to stand for 5 min until no water dropped. In this way, the floor water-holding capacity and water absorption rate were calculated from the difference of the dry and the re-wet floor sample weight. The maximal water-holding capacity of the forest floor was defined as the water-holding capacity after 24 hours. The unit of water-holding capacity was then calculated per unit of mm according to the area of floor plot. With these data, we can also find the relationship between the water-holding amount and the soaking time, and then test the regression using a 95% or 99% confidence level.

2.4 Data analysis

The data covering thickness, amount, maximal water-holding capacity and maximal water holding of unit weight of litter layer were subjected to a two-way ANOVA (floor layer and forest type) to assess their respective effects and also the interaction between them. The Tukey’s-b test was employed to test possible differences among the forest types. The relationship between water-holding amount, water absorption rate and the immersion time for the floor were modeled using a nonlinear regression equation. For statistical significance, P=0.05 was chosen. All analyses were conducted using SPSS v11.5.

3 Results and analyses

3.1 Thickness and amount of floor

In L, F, H and total floor layer, thickness and amount of floor were significantly different among the four plantations and the native coppice (P<0.001) (Fig.2). The thickness of L, F and total floor layer in Pt and Pa plantations was significantly higher than that in other plantations and the native coppice. However, plantation tree species substituting for native tree thicket did not have a significant effect on thickness of H floor layer (Fig.2a). The amounts of L, F, H and total floor layer in Pt and Pa plantations were also significantly higher than that in other plantations and the native coppice, with the exception of F floor layer, there was no difference between Pt and Lk plantations (Fig.2b).

3.2 Water-holding characteristics of floor

The maximal water-holding capacity and maximal water holding capacity per unit weight of floor were significantly influenced by plantation species (Fig.3). The maximal water-holding amount in F, H and total floor layer under Pt and Pa plantation were significantly higher than that under other plantations and the native coppice. However, there was not a significant difference in the L floor layer
between plantations and native coppice (Fig. 3a). The maximal water-holding capacity of floor unit weight in L layer under Lk and QC plantations was significantly higher than under Pt, Pa and Cj plantations. In the F and H floor layers, there was no significant difference in maximal water-holding capacity per unit weight among all selected stands, except for H floor layer. The maximal water-holding capacity per unit weight of floor in total floor layer was significantly higher under Pa and Lk than under Pt, Cj and QC (Fig. 3b).

### 3.3 The relationship between water-holding and the immersion time of the forest floor

#### 3.3.1 The relationship between water-holding amount and immersion time for the forest floor

The logarithmic regression had been expressed for the relationship between water holding quantity and immersion time of the forest floor (Fig. 4a, 4b and 4c and Table 2). We could find from Fig. 2a, b and c that the water-holding amount of the forest floor varied rapidly with immersion time in the first 8 h, but it varied less afterwards, so we take the water-holding amount of floor of immersion 24 h as the maximum water-holding capacity. There was a significant difference in the water-holding amount in L, F and H layers of different plantations and native coppice at the same time period. The trend was as follows: F>H>L.

For L, F and H layer floor, water-holding amount on the same time shows the trend: B>C>D>E>A, C>B≈ D>A≈ E and B≈C>D≈A>E, respectively.

#### 3.3.2 The relationship between water absorption rate and immersion time of the forest floor

The relationship between water absorption rate and immersion time for the forest floor fitted exponential regression (Fig. 5 and Table 3). Fig. 5a, 5b and 5c showed...
Fig. 4 Relationship between the water holding of the L (a), F (b), H (c) layer litter and immersion time.


Table 2 The relationship between the water holding quantity and the immersion time of floor (t<24 h)*.

<table>
<thead>
<tr>
<th>Forest types</th>
<th>L layer floor</th>
<th>F layer floor</th>
<th>H layer floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CJ</td>
<td>$y=0.0482\ln(x)+0.0537$ 0.948</td>
<td>$y=0.3844\ln(x)+0.8845$ 0.881</td>
<td>$y=0.223L(x)+0.5994$ 0.870</td>
</tr>
<tr>
<td>PT</td>
<td>$y=0.1879\ln(x)+0.3867$ 0.903</td>
<td>$y=0.5021\ln(x)+1.9099$ 0.948</td>
<td>$y=0.5170\ln(x)+2.309$ 0.943</td>
</tr>
<tr>
<td>PA</td>
<td>$y=0.1304\ln(x)+0.2141$ 0.883</td>
<td>$y=0.6997\ln(x)+2.9337$ 0.944</td>
<td>$y=0.7200\ln(x)+1.9383$ 0.918</td>
</tr>
<tr>
<td>LK</td>
<td>$y=0.1230\ln(x)+0.1369$ 0.934</td>
<td>$y=0.8098\ln(x)+1.2716$ 0.898</td>
<td>$y=0.3033\ln(x)+0.6482$ 0.824</td>
</tr>
<tr>
<td>QC</td>
<td>$y=0.0832\ln(x)+0.1118$ 0.944</td>
<td>$y=0.4000\ln(x)+0.6166$ 0.883</td>
<td>$y=0.1109\ln(x)+0.1976$ 0.931</td>
</tr>
</tbody>
</table>


Fig. 5 Relation between the water holding velocity of the L(a), F(b), H(c) layer litter and immersion time.


Table 3 The relationship between the water holding velocity and the immersion time of floor (t<24 h)*.

<table>
<thead>
<tr>
<th>Forest types</th>
<th>L layer floor</th>
<th>F layer floor</th>
<th>H layer floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CJ</td>
<td>$y=0.2753e^{0.0003x}$ 0.972</td>
<td>$y=2.6829e^{0.0003x}$ 0.989</td>
<td>$y=1.8728e^{-0.0003x}$ 0.995</td>
</tr>
<tr>
<td>PT</td>
<td>$y=0.9892e^{0.0003x}$ 0.997</td>
<td>$y=4.0643e^{-0.0003x}$ 0.996</td>
<td>$y=4.8681e^{-0.0003x}$ 0.996</td>
</tr>
<tr>
<td>PA</td>
<td>$y=0.6216e^{0.0003x}$ 0.999</td>
<td>$y=6.395e^{0.0003x}$ 0.999</td>
<td>$y=5.0805e^{-0.0003x}$ 0.994</td>
</tr>
<tr>
<td>LK</td>
<td>$y=0.4582e^{0.0003x}$ 0.990</td>
<td>$y=4.2523e^{0.0003x}$ 0.992</td>
<td>$y=1.917e^{-0.0003x}$ 0.987</td>
</tr>
<tr>
<td>QC</td>
<td>$y=0.3748e^{0.0003x}$ 0.990</td>
<td>$y=2.0024e^{0.0003x}$ 0.999</td>
<td>$y=0.7523e^{-0.0003x}$ 0.993</td>
</tr>
</tbody>
</table>

that the water absorption rates for L, F and H layers varied rapidly with immersion time in the first 8 h and varies less afterwards. Floor water absorption rates showed significant differences among the different plantations and native coppice. For L layer floor, water absorption rate of Pt plantation was higher than that of the other forests. For F layer floor, the maximum was Pa plantation, the second was Pt plantation and Lk plantation, the minimum was Cj plantation and native coppice. For H layer litter, regression curves of floor water absorption rate to the immersion time in Pa and Pt plantations almost overlapped and were significantly higher than that in Lk and Cj plantations. The lowest rate was found for native coppice.

4 Discussion and Conclusion

From the 1950s large areas of native forest were felled in west Sichuan (Wang and Wang 2007; Pang et al. 2011). A large number of single species coniferous plantations were established in clear-cut areas. Some partly native broad-leaved bush forest has been preserved (Pang et al. 2004; Wang and Wang 2007). However, few studies have been conducted on the effect of plantation forestry on the forest floor in the eastern of Tibetan Plateau.

Our research found that substitution of plantation species significantly affected forest hydrological characteristics. The thickness, amount and hydrological characteristics of forest floor in pure coniferous plantations, especially in Pa and Pt plantations, were higher than in native broad-leaved brushy forest (Figs. 2 and 3). Our results were consistent with Rao and Zhu (2007) and Zhang et al. (2006). These suggest that the forest floor of plantations significantly increased during almost 20 years of forest re-growth. In general, thickness and amount of forest floor after 20 years of forest re-growth in coniferous plantation were higher than that in broad-leaved plantation (Figs. 2 and 3). This was explained by the low decomposition rate in coniferous plantation (Lin et al. 2006). In previous research, Kong and Zheng (2004) indicated that the decomposition rate of litter was 0.55, 0.22 and 0.37 t h⁻¹ y⁻¹ in Cj, Pt and Lk plantation, respectively. However, annual litterfall was not significantly different between Cj plantation (3.79 t ha⁻¹) and Pt plantation (3.45 t ha⁻¹) (Kong and Zheng 2004). This is confirmed by the significant difference in thickness and quantity of forest floor among different litter horizons where coniferous plantations were substituted for native thicket (Fig. 2a and 2b). This suggests that the accumulation of floor in coniferous plantations can be primarily attributed to a low rate of decomposition and not greater litter fall.

Hydrological characteristics of the forest floor were significantly different among plantations species and native coppice (Figs. 4 and 5, Tables 2 and 3). The causes were due to differences in the amount of forest floor between different restoring plantations (Fig. 2b) and in maximal water holding per unit weight of floor of plantation species (Fig. 3b). Maximal water-holding capacity of the forest floor correlated positively with the amount of forest floor (R², 0.71, 0.87 and 0.89 in L, F and H horizon, respectively). Water absorption processes of the floor over time showed a logarithmic regression relationship within 20 h, which was consistent with the results of previous authors (Pang et al. 2005; Rao and Zhu 2007; Zhang et al. 2006). In contrast, we found that the water absorption rate and immersion time for litter showed an exponential regression relationship, inconsistent with other results (Rao and Zhu 2007; Zhang et al. 2006). They thought that the relationship exhibited power regression.

As we expected, the water absorption processes and rate significantly differed among selected stands and among different decomposition floor horizons. The difference in water absorption characteristics was influenced by leaf structure in various tree species (Cornelissen et al. 1999). Leaf anatomy also affects decomposition rate (Cornelissen et al. 1999). Dresbøll and Magid (2006) indicated that the anatomical arrangement of the tissue was just as important as the content of recalcitrant compounds of litter in determining decomposition rate. Some cell types functioned as barriers towards microbial degradation and immersence of water (Wilson and Mertens 1995), in particular, lignified tissues. However, the relative amounts of the constituent chemical structural compounds indicated different changes following the litter decomposition process (Martins et al. 1999). Broad-leaved and deciduous tree species have larger amounts of relatively easily decomposed compounds (alcohol/water soluble compounds and hemicellulose), while coniferous and evergreen trees contain higher proportions of difficult-to-decompose compounds (fats and waxes, Kjason lignin and cellulose) (Martins et al. 1999). An important parameter influencing water-holding capacity could be the degree of decomposition and the size and appearance of the particles remaining after degradation (Dresbøll and Magid 2006). It would be expected that plants with flexible structures such as helical secondary walls and a high content of fiber cells could enhance water retention due to improved contact between the larger particles of the litter enhancing the capillarity. Additionally, when cut and decomposed, these fibers may have a flexible structure improving the litter structure and thereby water retention capacity (Dresbøll and Magid 2006).

In summary, we presented a study of hydrological characteristics of the forest floor in different substituting plantations and native coppice. We found that there were significant differences in thickness and amount of floor among selected substituting plantations and native coppice. Differences in hydrological characteristics in restoring plantations were influenced by the amount of floor and maximal water-holding per unit weight of floor. Water
absorption processes and the rate of floor significantly differed among different plantations and decomposing floor horizons. Difference in water absorption was influenced by leaf structural traits in various tree species and the extent of decomposed litter. Our results suggest that litter amount in coniferous plantations is significantly higher than in deciduous broad-leaved plantation. This suggests a large amount of nutrient was held in the litter horizon, delaying return to the soil and utilization by plants. We could improve plantation management by accelerating litter decomposition. This can also significantly decrease the risk of fire. At the same time, maximal water-holding capacity of the floor in F and H horizons was significantly higher than L horizon. Influencing the microenvironment by promoting litter transformation from the L layer to F and H horizons would be a good method of improving plantation management.

Acknowledgements

We would like to acknowledge support from the National Natural Science Foundation of China (No. 40701181), the Strategic Leader in Science and Technology Projects (No. XDA05070306), the National Science & Technology Pillar Program in 12th Five-year Plan of China (No. 2011BAC09B04-02), Main Direction Program of Knowledge Innovation of CAS (No. KSCX2-EW-J-22), West Light Foundation of CAS, and Maokxian Ecological Station, Chengdu Institute of Biology. We also thank LENG Zhengyong, DENG Lijun and MA Jianhua of Sichuan Agricultural University for field sampling and laboratory help.

References


摘要：尽管森林地被物在保水与养分循环中扮演重要角色，但我们仍然对由植被转换引起的森林地被物的变化缺乏了解。为评价不同人工林替代乡土灌丛对森林地被物水文特性的影响，我们选择了4种人工林 (连香树 Cercidiphyllum japonicum [Cj], 油松 Pinus tabulaeformis [Pt], 华山松 Pinus armandi [Pa], 落叶松 Larix kaempferi [Lk]), 以次生乡土灌丛 (QC) (Quercus liaotungensis 和 Corylus heterophylla var. sutchuenensis) 为对照。人工林种植于1987年，初始密度为2500株 ha

我们发现针叶人工林地被物厚度和贮量明显大于次生灌丛地和阔叶人工林地。地被物最大持水量在各林地之间差异与厚度和贮量显示相同的趋势，我们认为其主要贡献因子为林地凋落物数量及单位重量凋落物的最大持水量差异。地被物吸水过程和吸水速率与浸泡时间分别呈对数与指数回归关系。吸水过程在各植被之间与地被物各层次之间明显不同，主要受各植被的凋落物叶结构与分解程度影响。我们的结果显示针叶林地被物储量明显高于阔叶林，这说明以针叶树种为优势的林地大量养分滞留在凋落物中，难于返还土壤被植物利用，同时，半分解层(F)和分解层(H)最大持水能力高于未分解层(L)，因此，改善林地微环境，促进L层地被物向F和H层转化，是改善人工林地被物水文功能的主要方法之一。

关键词：森林地被物；人工林替代；持水速率；持水量；生态恢复；青藏高原东缘