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ORIGINAL PAPER

Characteristics of runoff and sediment generation of forest vegetation on a hill slope by use of artificial rainfall apparatus

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Abstract: We studied the impact of forest vegetation on soil erosion, surface runoff, and sediment generation by using field simulated rainfall apparatus. We measured runoff and sediment generation of five 4.5 × 2.1 m runoff plots (a bare soil as a control; two *Pinus tabulaeformis* forest plots and two *Platycladus orientalis* forest with row spacing of 1 m × 1 m and 1.5 m × 1.5 m, respectively) in Beijing Jiu Feng National Forest Park under three rainfall intensities (0.42, 0.83, 1.26 mm per minute). Forest vegetation significantly reduced soil erosion and sediment yield. Mean total runoff volume in the four tree stand plots was 93% of that in the control plot, demonstrating the limited effectiveness of forest vegetation in runoff control. With increasing rainfall intensity, runoff reduction in forest plots declined from 28.32% to 2.1%. Similar trends in runoff coefficient and the relationship between runoff volume and rainfall duration was observed. Mean total sediment yield and mean sediment yield reduction rate under different treatments was 55.05% and 43.17% of those in the bare soil control plot, respectively. Rainfall intensity played an important role in runoff and sediment generation processes, and had a greater impact on runoff than on soil erosion and sediment generation. When considering several factors in runoff and sediment transport processes, the *P. tabulaeform* plot with row spacing at 1 × 1 m had a greater effect on soil and water conservation than did other forested plots.

Key words: soil erosion; forest vegetation; rainfall intensity; runoff; sediment

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Introduction

Soil erosion is a serious environmental and ecological problem in China. About five billion tons of soil are lost annually in China (Victor Hugo et al. 2008; Li et al. 2008). Soil erosion produces multiple types of serious damage to natural ecosystems and managed ecosystems such as crops, pastures, and forests. Typically it can reduce water-holding capacity and soil organic matter (Zhang 1999), leading to loss of nutrients and valuable soil biota, decline of species diversity, and the reduced ecosystem stability (Li et al. 2008).

Water erosion, including rain splash, surface runoff, and soil water infiltration, is the most widespread soil erosion type in China. Water erosion affects an area of about 1.61 × 10^7 km^2, accounting for 17% of China's land area. Runoff is a fundamental process in soil degradation, causing soil erosion and influencing the soil water balance and the hydrologic water cycle in ecosystems. Many experiments on runoff and erosion have been carried out in China (Zhang and Liang 1996; Wang et al. 2006; Li and Wang 2003; Yu et al. 2010; You and Li 2011) and internationally (Marston 1952; Branson and Owen 1970; Lang 1990; Ludwig and Tongway 1995; Bergkamp 1998; Cerdà 1999; Bochet 2000; Sanchez et al. 2002; Calvo et al. 2003; Casermeiro et al. 2004; Boer and Puigdefábregas 2005). The importance of vegetation in controlling water erosion is widely accepted. However, previous research focused on grassland or shrubland, and less attention has been paid to forests, especially forests with varied species compositions and planting densities.

We investigated the influence of tree species (*P. tabulaeformis*, *P. orientalis*) and their planting densities (1 × 1 m, 1.5 × 1.5 m) on regulation of soil erosion, and the hydrological responses to rainfall characteristics, especially to rainfall intensity. Our research objective was to explain the impact of forest vegetation on slope erosion processes.

Material and methods

Study site

The experimental site, Jiu Feng National Forest Park, is located in northwest Beijing (116°28′ E, 39°34′ N). The climatic zone is warm temperate with hot and rainy days in summer with mean annual temperature of 11.6°C. Mean annual precipitation is 630 mm, most of which falls as rain between June and September. Very intense and erosive rainfall events usually occur in autumn after the summer drought period. Dominant tree species include *Pinus tabulaeformis*, *Quercus variabilis*, and *Platycladus orientalis*, planted from the 1950s to 1960s. The soil is poorly developed and has little organic matter. Soil types change with altitude. The soil at 70-900 masl is cinnamon soil, while brown soils occur above 900 masl. The general slope aspect is northeast with average slope of 10 per cent.

Rainfall simulation apparatus

The artificial rainfall simulator was made jointly by Beijing Normal University and Beijing Jiaotong University in 2006 (Zhang et al. 2007; Xie et al. 2008), equipped with the Spraying Systems Co. Veejet 80150 Sprinkler, characterized by easily controlled, stable rainfall process with more than 0.8 rainfall evenness.

Experimental plots

Five 4.5 × 2.1 m runoff plots were constructed on the slope of 10% under two types of forest vegetation with different tree spacing within and between rows (Table 1). The litter layer was removed to observe the influence of forest vegetation on runoff and sediment generation. Experiments were carried out under the following conditions: mean raindrop diameter was less than 3 mm; the rain fell from a height of 2.5 m; three rainfall intensities (0.42, 0.83, 1.26 $mm\cdot min^{-1}$) were tested; rainfall duration was 1 h. Runoff and sediment yield were sampled at intervals of one minute during the rainfall period. Experiments were repeated twice at each rainfall intensity. After drying the sediment samples in the laboratory for 48 h at 50°C, the dry weight of eroded sediments and runoff volume were determined for each plot and rainfall event.

Table 1. Forest stands characteristics

Forest stands	Row spacing	Plot No.	Stand age (year)	Average tree height (m)	Based diameter (cm)	Coverage	Soil bulk density (g/cm^3)	Porosity (%)	Water content (%)
Control		1	-	-	-	-	1.57	59.24	17.62
Pinus tabulaeformis	1 m × 1 m	2	3	0.89	2.36	0.42	1.48	55.84	13.46
	1.5 m × 1.5 m	3	3	0.90	2.51	0.24	1.51	56.98	14.14
Platycladus orientalis	1 m × 1 m	4	3	1.14	1.71	0.18	1.42	53.58	15.60
	1.5 m × 1.5 m	5	3	1.11	1.70	0.11	1.55	58.49	13.24

Statistical analysis

Differences in runoff and sediment generation, soil loss by tree species (*P. tabulaeformis* [PT], *P. orientalis* [PO]), and tree planting densities (1 × 1 m, 1.5 × 1.5 m) were analyzed separately at all rainfall intensities. Variations in runoff and sediment generation were analyzed separately for the 30 erosive rainfall events using linear regression. By analysis of variance (ANOVA), differences were tested using the Listwise Statistics Dependent test at $p<0.01$ in SPSS. We then focused on rainfall intensity and assessed variations by Curve Fitting in SPSS, which explained the impact of rainfall intensity on runoff depth and total sediment yield. The relationship between accumulative runoff yield and accumulative sediment yield was analyzed by linear regression. Statistical analyses were performed using Excel and SPSS software.

Results and discussions

Impact of forest vegetation on slope runoff

Runoff generation and development process

Runoff from five runoff plots under two rainfall intensities is shown in Fig. 1 (As a similar fluctuation could be found under the rainfall intensity of 1.26 $mm\cdot min^{-1}$, we just listed the two figures to illustrate the runoff process). Obvious fluctuation in runoff volume was observed at the onset of rainfall. Runoff volume per minute from each treatment plot approached a steady state after 14 min and 8 min at rainfall intensities of 0.42 $mm\cdot min^{-1}$ and 0.83 $mm\cdot min^{-1}$, respectively. Runoff obviously increased when rainfall intensities were changed from 0.42 $mm\cdot min^{-1}$ to 0.83 $mm\cdot min^{-1}$. Runoff volume was lower from forest plots than from the bare soil control plot. The extent of reduction in runoff was affected by tree species and planting density. At rainfall intensity of 0.42 $mm\cdot min^{-1}$, the PT plot with row spacing at 1.5 × 1.5 m significantly reduced the runoff generation (1.99 $L\cdot min^{-1}$) compared with the bare soil control plot (3.45 $L\cdot min^{-1}$). At rainfall intensity of 0.83 $mm\cdot min^{-1}$, the PT plot with row spacing at 1 × 1 m had the lowest runoff volume per minute (6.17 $L\cdot min^{-1}$) of all treatments, significantly lower than that of the bare soil plot (7.27 $L\cdot min^{-1}$).

Runoff starting time

Runoff starting time from the two forested plots was significantly delayed as compared with the control plot and the delay effect declined with increase in rainfall intensity (Fig. 2). The delay of runoff start times between the control plot and the two forested plots were 129 s (PO) and 113 s (PT) at rainfall intensity of 0.42 $mm\cdot min^{-1}$. The delay was shortened to 49 s (PO) and 36 s

(PT) at rainfall intensity of 0.83 mm·min^{-1}. The delay was further shortened to 36 s (PO) and 23 s (PT) at rainfall intensity of 1.26 mm·min^{-1}. These results demonstrate that forest vegetation and rainfall intensity highly influenced the runoff starting time.

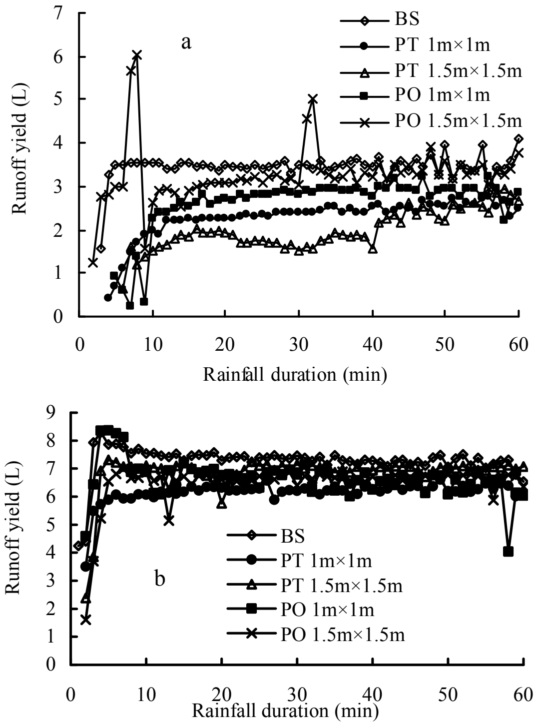

Fig. 1 Runoff generation process under different treatments. (a) rainfall intensity of 0.42 mm·min^{-1}, (b) rainfall intensity of 0.83 mm·min^{-1}. Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing of 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing of 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing of 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing of 1.5 m × 1.5 m.

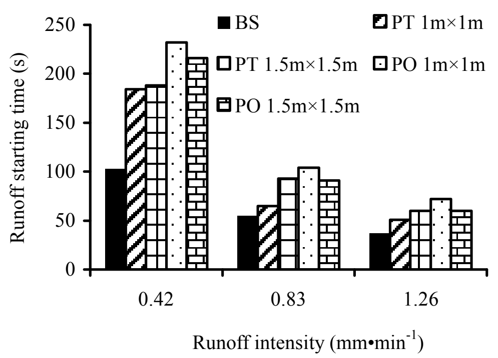

Fig. 2 Runoff starting time under three rainfall intensities in five plots. Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing of 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing of 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing of 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing of 1.5 m × 1.5 m.

Runoff coefficient and runoff volume reduction rate

Runoff coefficient and runoff volume reduction rate are two main indicators for runoff description. The runoff coefficient is the ratio of runoff depth to precipitation (The precipitation equals to rainfall intensity multiplies rainfall duration). The runoff coefficient for the bare soil plot was significantly higher than that for the forest plots at low precipitation of 25.2 mm (Table 2). PT 1 × 1 m and PO 1 × 1 m plots had low runoff coefficient values compared with the other two treatments. The trend in runoff volume reduction for the plot treatments is shown in Table 3. Mean runoff volume reduction was 28.32% under precipitation of 25.2 mm, and then declined to 2.1% under precipitation of 75.6 mm. Reduction in runoff volume declined substantially with increasing precipitation. Row spacing of 1 × 1 m showed higher efficiency in runoff volume reduction for both PT plot and PO plots. This suggests that row spacing of 1 × 1 m is a reasonable and efficient planting layout for controlling slope runoff. At the beginning of rainfall, forest canopy and interception protected the soil aggregation by reducing the kinetic energy of raindrops. The infiltration rate was high at the onset of rainfall when no runoff was recorded. The efficiency of the tree canopy in controlling runoff was higher at lower precipitation intensities. In contrast, when precipitation intensity increased, the stability of the soil declined due to raindrops directly impacting the soil surface. This reduced infiltration and led to larger volumes of runoff.

Table 2. Runoff coefficient under three precipitation intensities on five plots

Precipitation (mm)	Runoff coefficient (%)				
	BS	PT 1 m × 1 m	PT 1.5 m × 1.5 m	PO 1 m × 1 m	PO 1.5 m × 1.5 m
25.2	77.22	58.49	58.89	57.54	63.25
49.8	90.54	79.60	86.53	82.11	87.67
75.6	86.03	83.41	85.38	82.92	85.26

Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m

Table 3. Runoff volume reduction rate under three precipitation on five plots

Precipitation (mm)	Runoff volume reduction rate (%)			
	PT 1 m × 1 m	PT 1.5 m × 1.5 m	PO 1 m × 1 m	PT 1.5 m × 1.5 m
25.2	24.25	31.34	33.42	24.28
49.8	12.09	5.04	9.75	3.50
75.6	3.04	0.78	3.64	0.93

Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m

Relationship between cumulative runoff volume and rainfall duration

Cumulative runoff volume increased linearly with the increase in rainfall duration for all five plots (Fig. 3). The increase in runoff volume was even during the rainfall process. In contrast to cumulative runoff volume between bare soil and forested plots at rainfall intensity of 0.42 mm·min^{-1}, no significant difference was found between bare soil and forested plots under rainfall intensities of 0.83 mm·min^{-1} and 1.26 mm·min^{-1}. This result proved that the effectiveness of forest vegetation in reducing runoff volume depended largely on rainfall intensity. Moreover, *P. tabulaeformis* stands were more efficient than *P. orientalis* stands in controlling runoff volume.

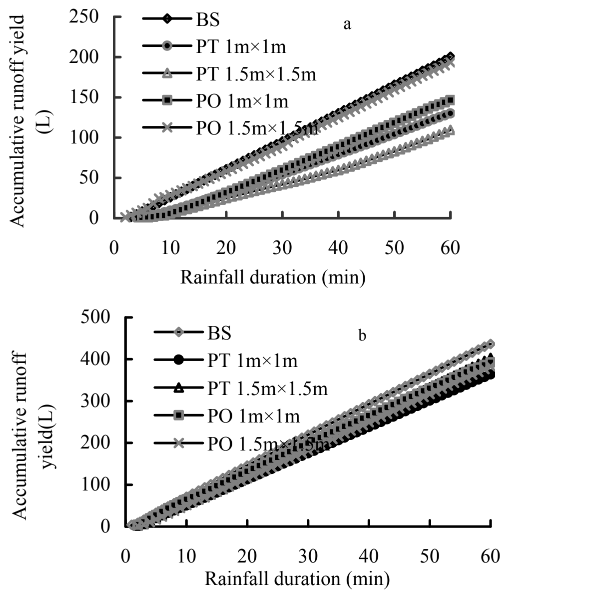

Fig. 3 The relationship between accumulative runoff volume and rainfall duration. (a) rainfall intensity 0.42mm·min^{-1}, (b) rainfall intensity 0.83mm·min^{-1}. Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m.

Impact of forest vegetations on soil erosion and sediment generation

Erosion process

Significant differences in erosion processes were observed between the control plot and the other four treatments. Obvious fluctuation in sediment yield was observed at the onset of rainfall events, except for PT 1 × 1 m and PO 1 × 1 m plots (Fig. 4). This was mainly because runoff volume was low at the initial phase, and fine sediments with small grain size were carried by runoff. However, continued splash erosion led to serious reduction of soil stability and sudden increase in sediment yield. The soil aggregation disintegrated into small soil particles and some sediments of middle to large grain sizes were carried by the high volume runoff.

The tree species and their planting densities obviously influenced soil loss and sediment yield per minute compared with the bare soil plot. Sediment yield from the control plot ranged from 42.7 g·min^{-1} to 183.5 g·min^{-1} (mean 127.07 g·min^{-1}) at rainfall intensity of 0.42 mm·min^{-1}. The four forested plots yielded 27.29, 69.75, 28.46, and 83.70 g·min^{-1} on average respectively. This confirmed that PT 1 × 1 m and PO 1 × 1 m were more effective at reducing soil loss and sediment yield. PT 1 m × 1 m plot was even more effective under rainfall intensity of 0.83 mm·min^{-1} with a sediment yield of 99.09 g·min^{-1} on average. This is mainly because the canopy cover intercepted rainfall and protected the soil surface against the impact of raindrops.

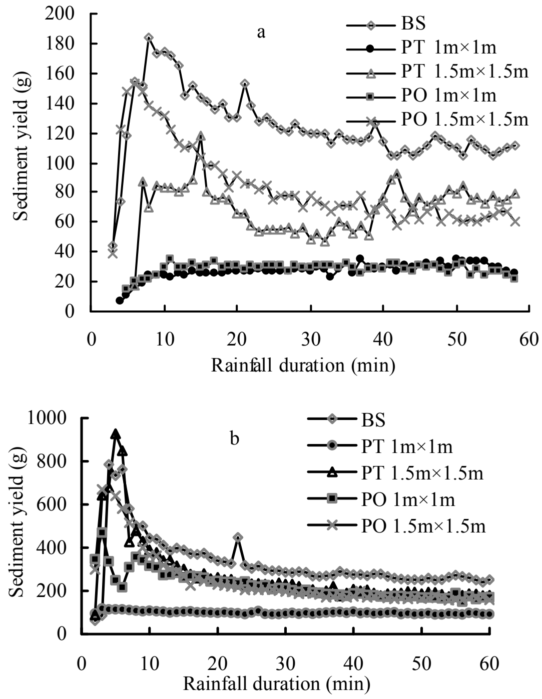

Fig. 4 Soil loss and sediment generation during the rainfall process. (a) Rainfall intensity was 0.42 mm·min^{-1}, (b) Rainfall intensity was 0.83mm·min^{-1}. Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m.

Sediment yield reduction rate of forest vegetation

To quantify the effectiveness of sediment reduction at forested plots, we calculated a sediment yield reduction rate (=1-sediment yield from forested plot/sediment yield from control plot) (Table 4). The reduction rates varied considerably by species. PT 1 × 1 m plot showed a significantly higher rate of sediment yield reduction (67.40% average for all rainfall intensities) than the other three treatments. Over the same period, significant differences between runoff volume reduction rate (Table 3) and sediment yield reduction rate were also identified; it indicated that forest vegetation had a greater influence on reducing soil loss and sediment reduction than reducing runoff volume.

Table 4. Sediment yield reduction of forest vegetation under different treatments

Rainfall intensity (mm·min^{-1})	Sediment yield reduction rate (%)			
	PT 1 m × 1 m	PT 1.5 m × 1.5 m	PO 1 m × 1 m	PO 1.5 m × 1.5 m
0.42	74.77	30.19	65.80	54.60
0.83	70.36	21.96	32.88	31.61
1.26	57.06	18.15	37.16	23.51

Plot treatments: PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m

Relationship between cumulative sediment yield and rainfall duration

There was a linear correlation between cumulative sediment yield and rainfall duration (Fig. 5), the change in rate depended on tree species and planting density. Cumulative sediment yield increased faster at the control plot than at the other four plots under different rainfall intensities. By contrast, cumulative sediment yield from PT 1 × 1 m and PO 1 × 1 m increased slowly at rainfall intensity of 0.42 mm·min^{-1}, this may be due to their canopy coverage and high planting density. PT 1 × 1 m was even more effective at rainfall intensity of 0.83 mm·min^{-1}.

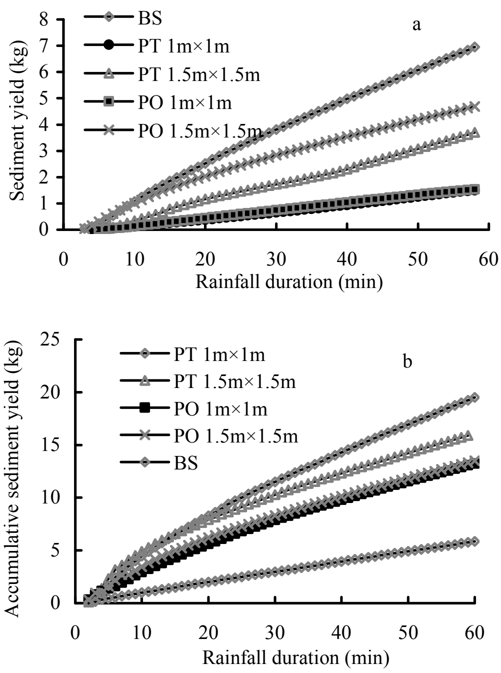

Fig. 5 Relationship between accumulative sediment yield and rainfall duration. (a) Rainfall intensity was 0.42 mm·min^{-1}, (b) Rainfall intensity was 0.83 mm·min^{-1}. Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m.

Relationship between accumulative runoff volume and accumulative sediment yield

At higher cumulative runoff volumes, more soil particles were carried by runoff under different treatments (Fig. 6). PT 1 × 1 m and PO 1 × 1 m generated less runoff volume and sediment yield than the other three plots at rainfall intensity of 0.42 mm·min^{-1} because of high planting density and canopy cover (coverage of 0.48 in PT 1 × 1 m plot). However, only PT 1 × 1 m plot was effective at reducing runoff volume and sediment yield at rainfall intensity of 0.83 mm·min^{-1}.This indicates that the effectiveness of a species in regulating erosion processes is strongly dependent on rainfall intensity.

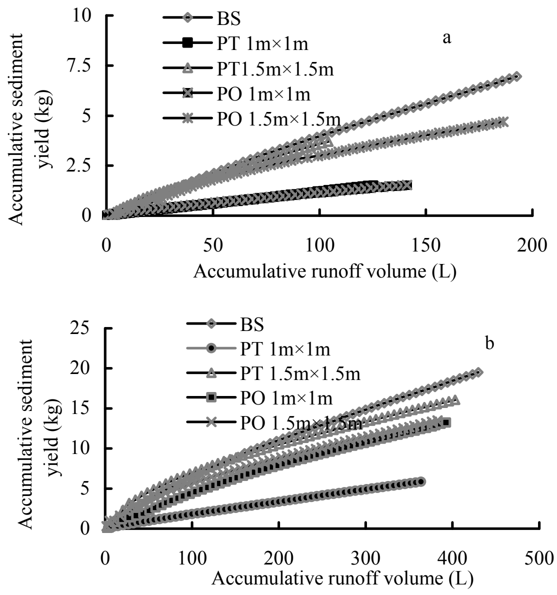

Fig. 6 Relationship between accumulative runoff volume and accumulative sediment yield. (a) Rainfall intensity was 0.42 mm·min^{-1}, (b) Rainfall intensity was 0.83mm·min^{-1}. Plot treatments: BS, bare soil; PT 1 m × 1 m, *Pinus tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *Pinus tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *Platycladus orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *Platycladus orientalis* with row spacing 1.5 m × 1.5 m.

Influence of rainfall intensity on runoff depth and total sediment yield

With increasing rainfall intensity, no significant difference in runoff depth was found between the five treatments, whereas there was an obvious difference in total sediment yield (Fig. 7). This implies that rainfall intensity played a larger role in sediment yield reduction than runoff depth reduction. Plots under tree cover were more effective in controlling sediment generation than runoff generation. Taking PT 1 × 1 m for example, at rainfall intensity of 0.42 mm·min^{-1}, its runoff depth was 75.76% of that from the control plot, while total sediment yield was only 25.33% of that from the control plot.

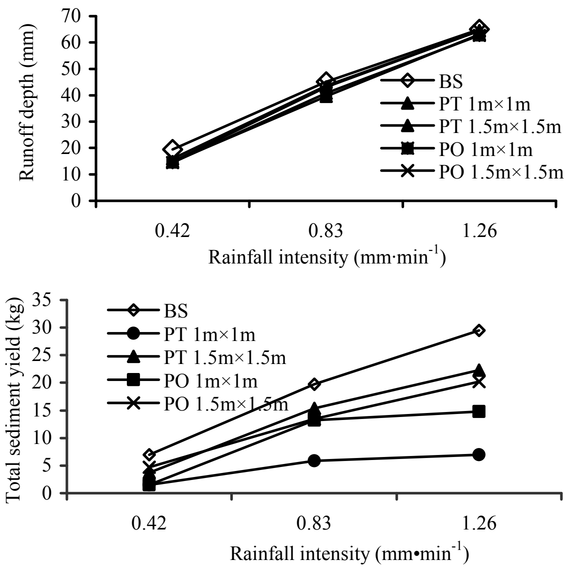

Fig. 7 Variation in runoff depth and total sediment yield at different rainfall intensities. Plot treatments: BS, bare soil; PT 1 m × 1 m, *P. tabulaeformis* with row spacing 1 m × 1 m; PT 1.5 m × 1.5 m, *P. tabulaeformis* with row spacing 1.5 m × 1.5 m; PO 1 m × 1 m, *P. orientalis* with row spacing 1 m × 1 m; PO 1.5 m × 1.5 m, *P. orientalis* with row spacing 1.5 m × 1.5 m.

Conclusion

Forest vegetation significantly influenced runoff generation, especially by reducing runoff yield and postponing runoff starting time. However, the effectiveness at runoff reduction declined significantly with increasing rainfall intensity. The *P. tabulaeformis* plot with row spacing 1.5 × 1.5 m was most effective in reducing total runoff volume at rainfall intensity of 0.42 mm·min^{-1}. Row spacing of 1 × 1 m was most effective for both *P. tabulaeformis* and *P. orientalis* at rainfall intensities of 0.83 and 1.26 mm·min^{-1}. Compared with runoff control, tree cover showed higher control capability on soil erosion and sediment yield reduction. Total sediment yield under tree cover was 55.05% of that from the control plot. Also the average sediment yield reduction rate was 43.17%, which was significantly higher than the average of runoff volume reduction rate of 12.67%. The *P. tabulaeformis* plot with row spacing 1 × 1 m was the most effective at reducing sediment yield with a sediment yield reduction rate of 67.40%. Forest vegetation was more effective at sediment reduction than at runoff reduction. Rainfall intensity plays an important role in the control of runoff generation and sediment yield. Increase in rainfall intensity had a stronger effect than tree cover on soil loss and runoff, runoff depth and total sediment yield. In conclusion, *P. tabulaeformis* with row spacing 1 × 1 m had a greater effect on soil and water conservation than the other treatments.

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