A preliminary investigation of surface runoff and soil properties in a moso-bamboo (Phyllostachys pubescens) forest in western Japan

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Abstract:

To clarify plot-scale runoff characteristics in bamboo forests, soil properties and surface runoff were measured in a preliminary study of a forested hillslope of moso-bamboo (Phyllostachys pubescens). Infiltration capacities and saturated hydraulic conductivities at 10, 30 and 50 cm depths were similar to or greater in the moso-bamboo forest than in an adjacent broad-leaved forest. This suggests that surface runoff rarely occurs in the moso-bamboo forest. However, surface runoff was observed in seven of 14 storm events. The surface runoff responses to rainfalls were relatively rapid and the amount of surface runoff per storm event depended largely on rainfall. The proportion of the total amount of surface runoff to the total rainfall during the observation period ranged from 19 to 33%, depending on the observation system. This indicates that the greater portion of rainfall infiltrated into the soil. A high density of roots in the surface soil suggests that part of the rainfall was impeded and passed laterally through the surface soil as preferential flow around the root mats and/or the rhizomes, thereby contributing to surface runoff.

KEYWORDS bamboo; biological invasion; biomat flow; forest management; hydrologic response; overland flow

INTRODUCTION

In Japan, particularly in western districts, bamboo forests have been expanding in recent years because of poor management practices (Nishikawa et al., 2005). The most common species of introduced bamboo in Japan is moso-bamboo (Phyllostachys pubescens), which is a large exotic species. Since bamboo forests generally form monocultures (e.g., Okutomi et al., 1996), there is concern that biological invasions and subsequent expansion of bamboos will reduce tree diversity and change landscapes. Therefore, several studies have focused on the ecological effects of bamboo invasions (Oliveira-Filho et al., 1994; Okutomi et al., 1996; O’Connor et al., 2000; Blundell et al., 2003).

Bamboos grow rhizomes laterally below ground. Rhizomes generate bamboo sprouts at the ground surface and thereby rapidly expand bamboo colonies (McClure, 1966). Bamboo dominant forests should have soil structures that differ from those in multi-stratified forests, such as those dominated by broad-leaved species. Since soil structure is closely related to the hydrological properties of forests, invasions of bamboos among other tree species could affect the water conservation functions of forests, including the control of storm flow volume and recharge of groundwater, in addition to tree diversity and landscapes. However, little information is available about how invasions of bamboos affect the water conservation functions of forests.

A few studies, mainly in moso-bamboo forests, have addressed our understanding of the hydrological properties of bamboo forests in order to evaluate their water conservation functions. Wang and Liu (1996) showed that the infiltration capacity in a moso-bamboo forest was greater than that in nearby Chinese fir plantations (Cunninghamia lanceolata) and that annual ‘slow runoff’ exceeded annual ‘quick runoff’. On the other hand, Torii (2007) reported that surface soils with a high density of roots represented high soil hardness and strong soil water repellency, and thus infiltration capacity could be low in a moso-bamboo forest. This suggests that infiltration-excess overland flow, i.e. Hortonian overland flow (Horton, 1933), readily occurs in moso-bamboo forests. Hiura et al. (2004) reported that the saturated hydraulic conductivity of surface soils under several types of moso-bamboo forests was extremely high, probably due to high soil macro-porosity, and predicted that intensively infiltrated rainwater through the surface soil might induce slope instability and subsequent failure in the bamboo forest. These studies show different understandings of hydrological properties in bamboo forests. This is because very few studies have focused on fundamental hydrological processes such as plot-scale runoff characteristics.

Our objective is to clarify plot-scale runoff characteristics as a first step toward a proper understanding of hydrological properties in bamboo forests. This study presents soil properties and preliminary results of surface runoff observations on a forested hillslope of moso-bamboo in western Japan. Soil properties in the moso-bamboo and an adjacent broad-leaved forest are compared and the amount and response times of surface runoff to rainfall in the forested hillslope of moso-bamboo are investigated.

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METHODS

The study sites were in moso-bamboo and adjacent broad-leaved forests located in Kasuya Research Forest, Kyushu University in Fukuoka prefecture, Japan (33°38'N, 130°31'E). Only brief summaries of the observation methods are presented here (refer to Supplement 1 for a detailed explanation).

A 6 m × 6 m plot was set up in each of the moso-bamboo and adjacent broad-leaved forests for soil property measurement. Each plot was subdivided into nine subplots (2 m × 2 m). Infiltration capacities of the soil surfaces were measured in the nine subplots of each forest. In the laboratory, soil porosity, mass of roots and saturated hydraulic conductivity ($K_s$) were measured using undisturbed soil samples at 10, 30 and 50 cm depths collected in three subplots of each forest.

In a forested hillslope of moso-bamboo, a bounded plot (width 1 m, slope length 2 m) was installed using corrugated panels to investigate surface runoff. It was located on the upper part of the short steep hillslope (slope gradient 47°, slope length ca. 5 m). Kuramoto et al. (unpublished) measured the total area of leaf litters by collecting all of them within the plot after the surface runoff observations and showed that the coverage of leaf litters (= total area of leaf litters/plot area) was 2.0 m$^2$. A plastic trough was installed at the lower edge of the plot to collect surface runoff. A plastic sheet (0.34 m$^2$) was installed on the litter layer at the lower part of the plot to lead surface runoff to the plastic trough. The upper edge of the sheet was inserted into the boundary between litter layer and surface soil. The plot includes a moso-bamboo with DBH of 11.1 cm. The amount of surface runoff was defined as the water volume (L) or depth (mm) collected by the plot. The surface runoff in this study indicates the flow on the surface of litter layer and/or the boundary between litter layer and surface soil. To investigate surface runoff in response to rainfalls, precipitation was measured by a tipping-bucket rain gauge at an open site located approximately 200 m west of the study sites.

A storm event was defined as rainfall divided by dry periods of more than 12 hours. The response time for each storm event was calculated as the lag between the peak rainfall and the peak surface runoff at 10-minute intervals. The runoff coefficient ($f$) in each storm event was calculated as the percentage of the amount of surface runoff to rainfall.

Statistical analyses were conducted using R, which is an open-source environment for statistical computing (The R Foundation for Statistical Computing).

RESULTS

Soil properties

Average infiltration rates in the first 15 seconds for the moso-bamboo and the adjacent broad-leaved forests were 338 and 328 mm hr$^{-1}$, respectively (Figure 1), and there was...
no significant difference between the forests (u-test, \( p = 0.965 \)). Final infiltration rates also did not significantly differ between the forests (u-test, \( p = 0.331 \)). The average final infiltration rate for the moso-bamboo forest (92.8 mm hr\(^{-1}\)) was 27 mm higher than that for the broad-leaved forest (65.9 mm hr\(^{-1}\)).

The average soil porosity for the moso-bamboo forest was very slightly (1.3–2.5%) higher than that for the broad-leaved forest at any soil depth (Figure 2a). There were no significant differences in soil porosities at any soil depth between the forests (u-test, \( p = 0.827 \) at 10 cm depth; \( p = 0.513 \) at 30 cm depth; \( p = 0.827 \) at 50 cm depth).

Although the mass of roots varied widely among the subplots, average values for the moso-bamboo forest were higher than those for the broad-leaved forest at any soil depth (Figure 2b). Also, the mass of roots for the moso-bamboo forest at 10 cm depth was significantly higher than that for the broad-leaved forest (u-test, \( p < 0.05 \)). In the moso-bamboo forest, the total mass of root at both 10 and 30 cm depths was greater than that at 50 cm depth.

The geometric means of \( K_s \) for the moso-bamboo forest did not differ among soil depths whereas those for the broad-leaved forest decreased with increasing soil depth (Figure 2c). The values of \( K_s \) at 10 and 30 cm depths did not significantly differ between the forests (u-test, \( p = 0.827 \) at 10 cm depth; \( p = 0.275 \) at 30 cm depth). However, \( K_s \) values at 50 cm depth for the moso-bamboo forest were significantly higher than those for the broad-leaved forests (u-test, \( p < 0.05 \)).

**Surface runoff**

Surface runoff was observed in seven of the observed 14 storm events (Table I). The total amount of surface runoff during the period was 48.3 mm, which was comparable to 33% of the total rainfall (146.1 mm).

The response time was relatively short, ranging from 0 to 50 minutes except for Event 3 (Table I). This indicates that surface runoff often occurred soon after the rainfall began.

There was a strong positive correlation between the amount of surface runoff and the rainfall per storm event (Figure 3; \( r = 0.99, p < 0.001 \)). The regression equation for the relationship showed that surface runoff occurred when the rainfall exceeded approximately 2.6 mm. The minimum and maximum values of \( f \) were 0 and 44%, respectively (Table I).

**DISCUSSION**

Both infiltration capacity and \( K_s \) for the moso-bamboo forest were equal to or greater than those for the adjacent broad-leaved forest (Figures 1 and 2c). Also, the geometric means of \( K_s \) for the moso-bamboo forest were almost constant regardless of soil depth. These results could be attributable to the high density of roots in the moso-bamboo forest. Noguchi *et al.* (1997) investigated the patterns of water flow in the soil based on dye techniques using white liquid paint and showed that vertical percolation was deflected laterally between the organic-rich layer and the B layer in a tropical rain forest in Peninsular Malaysia. They
attributed this to the fact that the organic-rich layer had a very high density of roots and was therefore highly permeable relative to the B layer. In the moso-bamboo forest, since surface soils have a high density of roots developing from the rhizomes, it is assumed that the occurrence of preferential flow towards the soil around the roots encourages vertical percolation. The soil properties suggest that Hortonian overland flow rarely occurs in the moso-bamboo forest.

In the forested hillslope of moso-bamboo, since the total amounts of surface runoff accounted for approximately 30% of the total rainfall during the observation period, it is most likely that the greater portion of rainfall infiltrated into the soil. In this preliminary investigation, we did not cover the plastic sheet in the surface runoff plot with a roof to avoid direct precipitation onto the sheet. Thus, it is possible that part of the rainfall was directly collected on the sheet and consequently the amount of surface runoff was overestimated. If the rainfall was completely collected on the sheet, the total volume of surface runoff during the observation period should be 49.7 L. On the other hand, the measured total volume was 96.6 L. Therefore, at least 46.9 L (28.3 mm: 19% of the total rainfall) was regarded as the total volume of surface runoff occurring on the hillslope. Since the canopy interception loss ratio (= interception loss/precipitation) in the bamboo forests has been reported as approximately 10% (Hattori and Abe, 1989; Wang and Liu, 1996; Lu et al., 2007; Onozawa et al., 2009), 60 to 70% of the total rainfall should infiltrate into the soil at our study site. Miyata et al. (2009) showed that arithmetic means of f values ranged from 4 to 13% and surface runoff rarely occurred in similar size plots as our study (width 0.5 m, slope length 2 m) on the forested hillslopes of Japanese cedar (Cryptomeria japonica) plantations and broad-leaved forests. This indicates a predominance of infiltration of rainfallwater to the forest soils. On the other hand, Miyata et al. (2007) confirmed that Hortonian overland flow occurred in the same size plots (width 1 m, slope length 2 m) on the forested hillslopes of a Japanese cypress (Chamaecyparis obtusa) plantation because of soil water repellency under antecedent dry conditions. They also showed that the amount of overland flow sometimes exceeded the rainfall (i.e. f > 100%) because rainwater accumulated as stemflow and intensively dripped from tree leaves and branches in the plantation during storm events. At our study site, the percentage of the total amount of surface runoff to the total rainfall was high compared with the other forested hillslopes described in Miyata et al. (2009). On the other hand, the values of f did not exceed 100% (Table 1) and were much lower than those observed in Miyata et al. (2007). These suggest that there is a different runoff mechanism in the forested hillslope of moso-bamboo than those in the other forested hillslopes.

The occurrence of surface runoff on the forested hillslope of moso-bamboo could be partially attributable to the high density of roots and rhizomes in the surface soil. In storm events, the massive form of roots as root mats, and rhizomes could locally impede infiltration of rainwater and change the flow of rainwater toward the soil around them, resulting in lateral preferential flow (Lu et al., 2007). Such preferential flow is referred to as ‘biomat’ flow, amounts of which can be several times greater than those of surface runoff (Sidle et al., 2007; Hirano et al., 2008), and ‘biomat’ in a moso-bamboo forest indicates dense networks of roots and rhizomes. At our study site, a rapid runoff response to rainfall was observed in storm events where the rainfall exceeded a certain amount (Table 1, Figure 3). Also, the amount of surface runoff depended largely on the rainfall and relatively large storm events showed values of f exceeding 40%. These results imply the occurrence of lateral preferential flow, i.e. biomat flow. Although we did not measure biomat flow, it is possible that biomat flow ran out of the partially exposed roots on the soil surfaces and contributed to the moderate amounts of surface runoff and the relatively rapid runoff response in the forested hillslope of moso-bamboo. In addition to living roots and rhizomes, decayed ones may affect the preferential flow path because they provide pipe channels in the soil. Therefore, it is also possible that infiltrated rainwater was locally concentrated into the pipe channels and generated pipe flow which contributed to the surface runoff in heavy storm events (Noguchi et al., 1997; Kobayashi et al., 2000). A very steep hillslope could also encourage the occurrence of surface runoff (e.g., Julien and Moglen, 1990; Lu et al., 2007).

In summary, much of the rainfall should infiltrate into the soil while a small portion of rainfall should generate surface runoff on the forested hillslope of moso-bamboo. This is consistent with the results of Wang and Liu (1996) and Hiura et al. (2004) who found that bamboo forest soils were highly permeable. As well, our study site had a high density of roots in the surface soil, which was similar to the site investigated by Torii (2007). The high density of roots could encourage preferential flow in both vertical and lateral directions and therefore contribute to the high permeability and the occurrence of surface runoff on the forested hillslope of moso-bamboo.

CONCLUSIONS

A comparison of soil properties between the moso-bamboo and adjacent broad-leaved forests revealed that the infiltration capacity and Ks were high in the moso-bamboo forest. This suggests that Hortonian overland flow should rarely occur in the moso-bamboo forest. However, in some storm events, relatively rapid runoff responses to rainfall were observed in the moso-bamboo forest. The amount of surface runoff in each storm event depended largely on the rainfall and the percentage of the total amount of surface runoff to the total rainfall during the observation period was relatively high. Since the surface soil had a high density of roots from the rhizomes, it is suggested that the occurrence of preferential flow towards the soil around the root mats and the rhizomes contributed to the moderate amounts of surface runoff and the relatively rapid runoff response in the moso-bamboo forest.

This study presented preliminary results of surface runoff observations at only one plot during winter periods. To better generalize plot-scale runoff characteristics in bamboo forests, improvements in the observation system and further investigations are needed (see Supplement 2).
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SUPPLEMENTS
S1. A detailed explanation for the observation methods.
S2. Perspectives.

REFERENCES
Blundell AG, Scatena FN, Wentsel R, Sommers W. 2003. Ecorisk assessment using indicators of sustainability: Invasive species in the Caribbean National Forest of Puerto Rico. Journal of Forestry 101: 14–19.

Hattori S, Abe T. 1989. Characteristics of canopy interception in a bamboo stand. Water Science 186: 34–53 (in Japanese).

Hirano T, Terajima T, Nakamura T, Aoki F, Sakai M. 2008. Surface and near-surface runoff at slopes of the unmanaged coniferous forests and the natural deciduous forests in Nariki nested catchment. Transactions, Japanese Geomorphological Union 29: 255–280 (in Japanese with English summary).

Hiura H, Arikawa T, Bahadur DD. 2004. Risk of sediment related disasters due to the abandoned expanding bamboo stands at the foot of slopes surrounding city area. Journal of the Japan Landslide Society 41(4): 1–12 (in Japanese with English summary).

Horton RE. 1933. The role of infiltration in the hydrologic cycle. Transactions of the American Geophysical Union 14: 446–460.

Julien PY, Moglen GE. 1990. Similarity and length scale for spatially varied overland flow. Water Resources Research 26: 1819–1832.

Kobayashi M, Onodera S, Kato M. 2000. Effect of a tree on water movement in a forest soil. Journal of the Japanese Forestry Society 82: 287–294 (in Japanese with English summary).

Lu S, Liu C, Hwang L, Wang C. 2007. Hydrological Characteristics of a Makino Bamboo Woodland in Central Taiwan. Taiwan Journal of Forest Science 22: 81–93.

McClure FA. 1966. The bamboo: a fresh perspective. Harvard University Press, Massachusetts; 347 pp.

Miyata S, Kosugi K, Gomi T, Onda Y, Mizuyama T. 2007. Surface runoff as affected by soil water repellency in a Japanese cypress forest. Hydrological Processes 21: 2365–2376. DOI: 10.1002/hyp.6749

Miyata S, Onda Y, Gomi T, Mizugaki S, Asai H, Hirano T, Fukuyama T, Kosugi K, Sidle RC, Terajima T, Hiramatsu S. 2009. Factors affecting generation of Hortonian overland flow in forested hillslopes: Analysis of observation results at three sites with different geology and rainfall characteristics. Journal of the Japanese Forestry Society 91: 398–407 (in Japanese with English summary). DOI: 10.4005/jjfs.91.398

Nishikawa R, Murakami T, Yoshida S, Mitsuda Y, Nagashima K, Mizoue N. 2005. Characteristic of temporal range shifts of bamboo stands according to adjacent landscape type. Journal of the Japanese Forestry Society 87: 402–409 (in Japanese with English summary).

Noguchi S, Abdul Rahim N, Kasran B, Tani M, Sammori T, Morisada K. 1997. Soil physical properties and preferential flow pathways in tropical rain forest, Bukit Tarek, Peninsular Malaysia. Journal of Forest Research 2: 115–120. DOI: 10.1007/BF02348479

O’connor PJ, Covich AP, Scatena FN, Loope LL. 2000. Non-indigenous bamboo along headwater streams of the Luquillo Mountains, Puerto Rico: leaf fall, aquatic leaf decay and patterns of invasion. Journal of Tropical Ecology 16: 499–516.

Okutomi K, Shinoda S, Fukuda H. 1996. Causal analysis of the invasion of broad-leaved forest by bamboo in Japan. Journal of Vegetation Science 7: 723–728.

Oliveira-Filho AT, Vilela EA, Gavilanes ML, Carvalho DA. 1994. Effect of flooding regime and understorey bamboos on the physiognomy and tree species composition of a tropical semideciduous forest in Southeastern Brazil. Plant Ecology 113: 99–124. DOI: 10.1007/BF00044229

Onozawa Y, Chiwa M, Komatsu H, Otsuki K. 2009. Rainfall interception in a moso-bamboo (Phyllostachys pubescens) forest. Journal of Forest Research 14: 111–116. DOI: 10.1007/s10310-008-0108-2

Sidle RC, Hirano T, Gomi T, Terajima T. 2007. Hortonian overland flow from Japanese forest plantations—an aberration, the real thing, or something in between? Hydrological Processes 21: 3237–3247. DOI: 10.1002/hyp.6876

Tori A. 2007. Elucidation of effects of bamboo forest extension on water retention characteristics of soil. Environmental Information Science 35: 80–81 (in Japanese).

Wang Y, Liu Y. 1995. Hydrological characteristics of a moso-bamboo (Phyllostachys pubescens) forest in South China. Hydrological Processes 9: 797–808. DOI: 10.1002/hyp.3360090706