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Characteristics of soil erosion in a moso-bamboo forest of western Japan: Comparison with a broadleaved forest and a coniferous forest

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ABSTRACT

In Japan, moso-bamboo (*Phyllostachys edulis* (Carrière) J. Houz.), an invasive species, has spread into and replaced surrounding broadleaved and coniferous forests because of the inactive management of moso-bamboo forests. Some local governments in Japan have speculated about an increase in soil erosion caused by the replacement with moso-bamboo forests. To evaluate the impact of such replacement on soil erosion, the soil erosion rate in a moso-bamboo forest was compared with those in an evergreen broadleaved forest and a coniferous forest. We established three plots (width 1 m, length ca. 2 m) in each forest and measured overland flow and soil erosion in two continuous periods (Period I: July 26, 2012–April 26, 2013; Period II: April 26, 2013–July 17, 2014). In Period I, the soil erosion rate in the moso-bamboo forest (0.08–0.10 $g\,m^{-2}\,mm^{-1}$) was not significantly higher than that in the broadleaved forest (0.27–0.55 $g\,m^{-2}\,mm^{-1}$) and the coniferous forest (0.16–0.27 $g\,m^{-2}\,mm^{-1}$). In Period II, we removed understory vegetation and litter from two of the three plots in each forest. In Period II, the plots with such removal had higher soil erosion rates than the control plots. The soil erosion rate for the removal plots of the moso-bamboo forest was less than half of those of the broadleaved and coniferous forests. Although rock fragment cover on the soil surface and shear strength of the topsoil did not differ significantly among the three forests, root density in the moso-bamboo forest was much greater than those in the broadleaved and coniferous forests. These results suggest that a large amount of roots in moso-bamboo forests could reduce soil erosion there. The findings of this study show that moso-bamboo forests have strong resistance against soil erosion, so the replacement of broadleaved and coniferous forests by moso-bamboo forests would not seem to imply an increase in soil erosion.

1. Introduction

Soil erosion by water involves two phases, detachment and transport of soil particles, which are caused by raindrops and overland flows (Morgan, 2005). Although canopy interception loss reduces the amount of rainfall reaching the floor in forests (Shinohara et al., 2013, 2015), raindrop size in forests is larger than that of natural rainfall (Nanko et al., 2006; Levia et al., 2017). Therefore, the kinetic energy of raindrops in mature forests tends to be greater than that of natural rainfall (Tsukamoto, 1976; Nanko et al., 2004). However, severe soil erosion generally does not occur on forested slopes with a protective ground cover by understory vegetation and/or litter on the ground (Sidle et al., 2006). There are generally negative relations between this protective ground cover and soil erosion rate in forests (Li et al., 2015; Miura et al., 2015). The ground cover protects the soil surface from raindrops with high kinetic energy (Chapman, 1948; Calder et al., 1993; Liu et al., 2016).

Monoculture forests with limited protective ground cover, however, have a risk of suffering from severe soil erosion (Seitz et al., 2016). In Japan, severe soil erosion has been reported in slopes covered by unmanaged Japanese cypress (*Chamaecyparis obtusa* (Siebold & Zucc.) Endl.) plantations (Miura et al., 2003, 2015; Mizugaki et al., 2010; Onda et al., 2010). Japanese plantations primarily consist of two coniferous species, such as Japanese cypress and Japanese cedar (*Cryptomeria japonica* D. Don). Recently, forest practices have been abandoned in Japanese plantations because of low timber prices and increased employment costs (Komatsu et al., 2010). Unlike in managed forests, little understory vegetation is found in unmanaged forests because the ground receives little sunshine due to the dense canopy. In addition, in Japanese cypress forests, litter layers are insufficiently developed (Ide

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et al., 2009). Litter undergoes active decomposition (Ichikawa et al., 2006). Furthermore, leaves disperse easily and are readily washed by rainfall within a short period after falling (Sakai and Inoue, 1988).

Although soil erosion has been observed in various types of Japanese forests including evergreen broadleaved forests and Japanese cedar plantations, severe soil erosion has been identified only in Japanese cypress plantations (Miura et al., 2003; Nanko et al., 2008). Wakiyama et al. (2010) observed lower soil erosion in evergreen broadleaved forests and Japanese cedar plantations than in Japanese cypress plantations.

Moso-bamboo (*Phyllostachys edulis* (Carrière) J. Houz.) is one of the largest species of bamboo and grows in Asian countries (Yuen et al., 2017). In Japan, moso-bamboo is a non-native invasive species; it was introduced from China in the 1700s. The shoots of moso-bamboo were harvested until recently; however, these forests started to be abandoned because of increasing bamboo imports and decreasing profitability. In western Japan, moso-bamboo forests have spread into and replaced surrounding broadleaved and coniferous forests (Okutomi et al., 1996; Isagi and Torii, 1998; Suzuki and Nakagoshi, 2008) because moso-bamboo has extremely high productivity and active rhizomatous clonal growth (Fukushima et al., 2015; Song et al., 2017). Some local governments in Japan have speculated about a decrease in ecosystem services associated with hydrology, soil erosion, and biodiversity due to the expansion of moso-bamboo forests, and conducted clearcutting of them (Shinohara et al., 2014). Understory vegetation rarely grows in moso-bamboo forests (Suzuki, 2010). Since the lack of understory vegetation presents a similar situation as in unmanaged Japanese cypress forests, the risk of soil erosion in moso-bamboo forests could be relatively high compared to other forest types in Japan. However, no studies have examined the rate of soil erosion in moso-bamboo forests.

Against this background, the objective of this study was to analyze the hypothesis that the expansion of moso bamboo forests is associated with an increased risk of soil erosion. We measured the soil erosion rate in a moso-bamboo forest and as well as in a surrounding evergreen broadleaved forest consisting of camphor trees in the canopy layer and in a neighboring Japanese cedar plantation. We inferred that if soil erosion in the moso-bamboo forest was not higher than that in the evergreen broadleaved forest and Japanese cedar plantation, the risk of increased soil erosion due to the expansion of moso-bamboo forests should be relatively low. Most of the forest floor of these three forests was covered by litter. To obtain a better understanding of the role of the understory vegetation and litter layer in mitigating soil erosion, we also measured the soil erosion rate after removal of these protective ground cover elements in some of the plots in each forest. As soil erosion would be affected not only by the protective ground cover but also by roots, the rock fragment cover, and the soil shear strength, we compared these three factors among the three forests.

2. Material and methods

2.1. Study area

This study was conducted in a moso-bamboo forest and two adjacent forests, namely, a natural evergreen broadleaved forest and a Japanese cedar plantation, in Kasuya Research Forest (33°38′N, 130°33′E) of Kyushu University, Fukuoka, Japan (Fig. 1). At the nearest long-term meteorological observatory (Fukuoka, 15 km west of the site), the annual mean air temperature (1981–2010) was 16.0–18.1 °C with the mean value of 17 °C and the annual precipitation (1981–2010) was 891–2085 mm with the mean value of 1612 mm.

The soil and underlying bedrock at this site are brown forest soil and Sangun metamorphic rock, respectively. The topsoil (depth of approximately 0–5 cm) is silt loam (Ichihashi et al., 2015), based on the United States Department of Agriculture (Soil Survey Staff, 1975). Soil depths at the moso-bamboo, evergreen broadleaved, and Japanese cedar forests were approximately 40, 50, and 90 cm, respectively. There were no significant differences in saturated hydraulic conductivity, soil porosity, and bulk density among the three forests (ANOVA, $P > 0.05$; Table 1). These comparisons were conducted using undisturbed samples taken from the topsoil (depth of 0–5 cm) at five random locations using a cylindrical sampler with a volume of 100 cm^3 (diameter = 5.0 cm; height = 5.1 cm). Saturated hydraulic conductivity was measured using the falling-head method. Hardness of the topsoil (i.e., soil hardness) was greatest for the moso-bamboo forest, followed by the Japanese cedar forest, and then the evergreen broadleaved forest (Table 1). These differences were significant (ANOVA followed by Tukey's post-hoc test; $P < 0.05$). The soil hardness was measured at 14 random locations for each forest using Yamanaka System Hardness Sensors (Fujiwara Scientific Co. Ltd., Tokyo, Japan).

In the moso-bamboo forest, the canopy comprises only moso-bamboo plants. The stem (clum) density, the mean diameter at breast height (DBH), and the basal area are 11,000 stems ha^{-1}, 10.9 cm, and 105.2 $m^2 ha^{-1}$, respectively. The evergreen broadleaved forest is mainly composed of camphor threes such as *Machilus thunbergii* Siebold et Zucc. and *Cinnamomum camphora* (L.) J. Presl for the canopy layer, Japanese blue oak (*Quercus glauca* Thunb.) for the sub-canopy layer, and Japanese laurel (*Aucuba japonica* Thunb.) for the shrub layer. Stem density, mean DBH, and basal area of trees with DBH of > 10 cm are 1117 stems ha^{-1}, 16.6 cm, and 42.9 $m^2 ha^{-1}$, respectively (Ichihashi et al., 2017). In the Japanese cedar forest, the canopy comprises only Japanese cedar. Its stem density, mean DBH, and basal area are 1400 stems ha^{-1}, 30.3 cm, and 98.9 $m^2 ha^{-1}$, respectively. A large part of forest floor in the three sites is covered by litter. Some understory plants are present in the evergreen broadleaved and Japanese cedar forests in contrast with that in the moso-bamboo forest.

2.2. Overland flow and soil erosion measurements

To measure overland flow and soil erosion, we established three bounded plots (width 1 m, length ca. 2 m) using corrugated panels for each forest (Fig. 1; Table 2). The three plots were situated close to each other in each forest. We refer to the three plots for the moso-bamboo forest as M1–3, those for the evergreen broadleaved forest as E1–3, and those for the Japanese cedar forest as C1–3. The slope gradient for the three plots in the moso-bamboo forest (45°–49°) was slightly steeper than that for the other six plots (38°–42°). No trees were included in the six plots in the evergreen broadleaved and Japanese cedar forests. A bamboo was included in M1 and M3 but not in M2. Due to the high bamboo density, it was not possible to establish the plot without a bamboo. The percentage cover by understory vegetation and litter in each of the plots was 47%–75% (Table 2). The percentage cover was determined using three photos taken to cover the entire area of each plot on November 9, 2012, with the images handled using the Image J image processing software (National Institutes of Health, Bethesda, MD, USA). The percentage cover values did not differ significantly among the three forest types.

A plastic trough was installed at the lower edge of each plot. An aluminum plate was installed between the soil surface and the trough. The trough was connected to a 90-L reservoir tank using a plastic hose. Water in the trough (i.e., overland flow) was transferred into the reservoir tank. We installed a 0.1-cm mesh screen on the trough at the outlet. We collected sediment and litter on the screen and in the trough and measured the amount of runoff water. Runoff water with sediment in the reservoir was collected using a 500-ml plastic bottle after thoroughly mixing the water in the reservoir. We then discarded the water and cleaned the reservoir using paper towels. We divided the samples collected from the trough into fine soil (particle size < 2.0 mm), gravel (particle size ≥ 2.0 mm), and litter. The divided samples were dried at 105 °C for 24 h in a dry oven and weighed in the laboratory. We calculated the amount of eroded sediment in the reservoir from the sediment concentration in a 500-ml bottle and the amount of runoff water. The runoff water with sediment was dried in an oven and the dried