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Characteristics of overland flow generation on steep forested hillslopes of central Japan

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Summary Overland flow generation was monitored in large plots (8 × 25 m) on four hillslopes in a 4.9-ha catchment in Mie Prefecture, Japan. Three Japanese cypress (hinoki, *Chamaecyparis obtusa*) treatments (including three different understory conditions) and one deciduous forest treatment were studied. For all plots, including deciduous hillslopes, we observed overland flow even for small storm events (<10 mm in total precipitation). The mean runoff coefficients in dense Japanese cypress plots with sparse understory were highest (13.0%) followed by dense Japanese cypress with fern ground cover (6.7%), and coefficients in managed cypress and deciduous forest were 3.6% and 1.2%, respectively. The runoff coefficients tended to be higher during storms that were preceded by dry conditions. High soil water repellency initially occurred in Japanese cypress forests between the litter and mineral soil horizon and might have been partly responsible for overland flow generation. During storms with total precipitation >180 mm, runoff from Japanese cypress plots with dense fern understory exhibited a delayed and higher peak associated with return flow. The dominance of hillslope-scale flow contribution to catchment runoff was also affected by changes in the dominance of overland flow and return flow. Understory vegetation cover and the availability of a litter layer altered the amount of overland flow, which was mediated by soil water repellency and soil moisture. Observations at the hillslope scale are essential for conceptualization of runoff mechanisms and pathways in forested headwaters.

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Introduction

The condition of the soil surface controls the flux of water from the atmosphere into the soil matrix. Although infiltration-excess overland flow is a major stormflow generation process that results in a quick runoff response in some catchments (Horton, 1933), most forest soils have high infiltrability that promote subsurface and saturated overland flow as the dominant runoff mechanisms (Tsukamoto, 1963; Hewlett and Hibbert, 1967; Dunne and Black, 1970). Hortonian overland flow may occur on hillslopes affected by fire (e.g., Shakesby et al., 1993), roads and skid trails (e.g., Ziegler and Giambelluca, 1997), and prolonged drought (e.g., Zehe et al., 2007). The extent and continuity of induced hydrophobicity and resultant Hortonian overland runoff from burnt forest soils depends on the severity of the fire (Doerr et al., 1998; Cannon and Reneau, 2000). Overland flow has also been observed in Japanese cypress (hinoki, *Chamaecyparis obtusa*) forests with sparse understory vegetation cover (Onda and Yukawa, 1994; Miura et al., 2002; Nanko et al., 2008; Fukuyama et al., 2008; Gomi et al., 2008). On hillslopes with Japanese cypress stands, soil water repellency at the 5–10 cm depth below the soil surface also promotes overland flow (Kobayashi and Shimizu, 2007; Miyata et al., 2007). Flow above the mineral soil – organic horizon interface associated with transient saturation of the surface of mineral soil may commonly provide a rapid pathway for the runoff of storm water and nutrients from forested hillslopes that have organic horizons and well-developed root networks (Burch et al., 1989; Buttle and Turcotte, 1999; Baudoux et al., 2006; Scherrer et al., 2007; Sidle et al., 2007).

Overland flow from hillslopes is highly variable both spatially and temporally. Microtopographic patterns (e.g., surface depressions, roughness) cause spatial variability in ponding and preferential infiltration (Julien and Moglen, 1990; Dunne et al., 1991). Spatially variable soil moisture and soil physical properties (e.g., clay composition, buried organic matter) alter the occurrence and pathways of both overland and subsurface flow (Sharma et al., 1980; Burch et al., 1989; Sidle et al., 2000; Ziegler et al., 2001; Uchida et al., 1999; Godsey et al., 2004). Water-repellent soils may produce localized areas of high Hortonian overland flow and preferential vertical infiltration (Imerson et al., 1992; Kobayashi and Shimizu, 2007). Such effects may be obscured at the hillslope scale due to infiltration 'hot spots' or lack of connectivity between localized overland flow source areas (Gomi et al., 2008). The effect of hillslope position has generally not been considered in small-scale runoff studies, although runoff mechanisms likely differ as a result of such influences on soil moisture (Gascuel-Odoux et al., 1996; Hung et al., 2001). The general decreases noted in runoff coefficients at increasing hillslope lengths also suggest scaling phenomenon of overland flow generation (van de Giesen et al., 2000; Joel et al., 2002; Cerden et al., 2004; Gomi et al., 2008). Yet, the effects of these phenomena of overland flow generation on hillslope- to catchment-scale storm runoff processes are unknown (Sidle et al., 2007; Gomi et al., 2008). Current hydrological models that use empirical formulae based on small plots, averaged catchment-scale analogues, or both may overestimate the importance of overland flow contributions to streams.

We examined hillslope-scale overland flow generation in large, unreplicated hillslope-scale plots for various conditions of understory and overstory vegetation cover in Japanese cypress forests and in an adjacent deciduous forest. Our objectives were to quantify the amount of overland flow generation on hillslopes with various forest and understory conditions. We also evaluated the role of vegetation ground cover on overland flow generation from steep forested hillslopes. We then demonstrate the role of vegetation ground cover on overland flow generation at the hillslope scale.

Study site and methods

The study was conducted within a 4.9-ha catchment (catchment 1) located in central Mie Prefecture (34°21′ N, 136°25′ E; altitude: 100–260 m), south-central Japan (Fig. 1). The climate of this area is moist and temperate, with mean annual precipitation of approximately 2000 mm and mean annual air temperature of 14 °C. The rainfall regime is bimodal: the Baiu season from late May through June, and the typhoon season from late August through October. Soils are Cambisols (brown forest soils in the Japanese classification) ranging in depth from 0.6 to 1.8 m. The soils are relatively shallow on lower hillslopes and thicker near mid-slope and ridgeline positions (Fig. 2). The combined A and B horizons are approximately 25–30 cm thick, underlain by a C horizon that is typically >35 cm thick. Thickness of the litter layer varies from 0 to 3.5 cm, depending on the vegetation cover (Table 1). The catchment is deeply incised with a dominant hillslope gradient of 35°–45°. The forest is predominantly a 40-yr-old stand of Japanese cypress (hinoki, *Chamaecyparis obtusa*), with a few small inclusions of Japanese cedar (sugi, *Cryptomeria japonica*) and broadleaf forest. The dominant understory vegetation is fern (*Gleichenia japonica*) and evergreen shrubs (e.g., *Cleyera japonica*).

A nested monitoring network was installed in the catchment in spring 2004 to evaluate runoff and sediment transport from Japanese cypress stands of different density and management legacies. Each subcatchment (1.2–0.2 ha in area) was characterized based on management legacy, stand density, and understory vegetation cover (Table 1; Fig. 3). Catchment 5 had dense (4500 stems/ha) cypress cover with sparse understory vegetation (Fig. 3a), whereas catchment 4 had less dense (3500 stems/ha) cypress and more abundant fern understory (Fig. 3b). Because of thinning after plantation establishment, the stand in catchment 2 had fewer cypress stems (1500 stems/ha) and the largest average stand diameter of all cypress stands (Fig. 3c). Thinning at this area was conducted by chainsaw, and logs were manually removed by foresters. Thus, soil surface disturbance and compaction was minimized, and the litter layer remained on the hillslope. Adjacent to catchment 1, we also monitored a small catchment (catchment 8) that was covered by deciduous forest (Fig. 3d).

Hillslope plots were established within the four subcatchments to monitor overland flow. Plot 1 was located within catchment 5, plot 2 in catchment 4, plot 3 in catchment 2, and plot 4 in catchment 8 (Fig. 3). Hillslopes with predominantly planar topography and little internal roughness (e.g., extensive woody debris, boulders, slope breaks)