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Soil physical characteristics of a degraded tropical grassland and a 'reforest': Implications for runoff generation

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ABSTRACT

Imperata grassland soils are widely perceived as having poor physical and chemical properties that render them unproductive and prone to erosion. They are therefore increasingly targeted for reforestation across the tropics. To better understand how reforestation and forest growth affect soil hydrological processes we compared the soil physical characteristics for an *Imperata* grassland and a 23-year-old 'reforest' on Leyte Island, the Philippines. Saturated hydraulic conductivity (K_{sat}) was determined in the field (Amoozemeter, 20–90 cm depth) and the laboratory (small-core permeametry). Core-based values of K_{sat} were (much) lower than field-based values, suggesting macropores were not sampled adequately with the small cores. K_{sat} decreased exponentially with depth in both land-cover types, with a median field-measured K_{sat} of the grassland of 2.1 mm h^{-1} at the surface and 2.9 mm h^{-1} at 20–40 cm depth, declining to ≤1 mm h^{-1} below 60 cm. Corresponding values for the reforest were 59 (at 20 cm), 37 (at 40 cm) and 7.3 mm h^{-1} (at 60–100 cm depth). Reforest K_{sat}-values down to 60 cm depth were significantly higher than corresponding values in the grassland, but the difference disappeared at 90 cm depth. Organic carbon content in the top 40 cm of soil was slightly higher in the reforest than the grassland. Bulk density was higher and porosity marginally lower in the grassland than the reforest at all depths considered. The median five-min rainfall intensity (June 2013–May 2014) was 3.2 mm h^{-1}, suggesting that > 50% of the rainfall might generate Hortonian overland flow in the grassland. Overland flow is unlikely in the reforest where lateral flow is likely to be generated around 60 cm depth for ~30% of rain-time, versus 2–3% between 20 and 60 cm. Within the limitations of the space-for-time substitution approach, these results suggest that 23 years of forest development at Manobo had a positive effect on hillslope hydrological functioning.

1. Introduction

Heavy logging and decades of increasingly intensive slash-and-burn agriculture have turned extensive areas of once lush tropical forest lands to fire-climax grasslands dominated by *Imperata cylindrica* (L.) P. Beauv. (spear grass) across South-east Asia. Using land-cover inventory data from the 1980s and early 1990s, Garrity et al. (1997) estimated the total area under *Imperata* grassland in South- and South-east Asia at the time at about 35 million ha (range: 21–57 million ha), adding that the actual area is likely larger because grassland patches that were too small to appear on national land-use maps were excluded from the analysis. Furthermore, the frequency of wildfires in insular South-east Asia has increased markedly over the last two to three decades due to an intensification of both regional climate change (notably the frequency of El Niño-Southern Oscillation events) and forest clearing for extractive plantations and agriculture (Field et al., 2009; Hoscilo et al., 2011; Page and Hooijer, 2016) which is likely to have expanded the area under fire-climax grasslands even further (cf. Murniati, 2002; Van der Kamp et al., 2009). *Imperata* grassland soils are generally perceived to have poor physical properties, low organic matter and nutrient

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contents, and high exchangeable aluminium concentrations that render them unproductive and prone to erosion (Costales, 1979; Ohta, 1990; Concepcion and Samar, 1995; Santoso et al., 1997; Handayani et al., 2012). In addition, burning and grazing are known to intensify surface runoff and sediment production (Coster, 1938; Jasmin, 1976; Chandler and Walter, 1998). As a result, fire-climax grasslands across the tropics are increasingly targeted for conversion to more productive and environmentally benign forms of land use, such as reforestation (Otsamo, 2000; Wishnie et al., 2007; Ancog et al., 2016) and – in areas with high land pressure – cultivation systems that integrate trees with agricultural crops and soil conservation measures (Van Noordwijk et al., 1997; Murniati, 2002; Snelder and Lasco, 2008; Handayani et al., 2012). While the recurring fire typically associated with these grasslands (Malmer et al., 2005) usually prevents the re-establishment of forest through natural regeneration, *Imperata* can be shaded out by planting fast-growing trees in combination with intensive initial soil management (Otsamo, 2000; Murniati, 2002). The shading afforded by the new trees not only reduces the competitive ability of the grasses but also promotes the germination and subsequent development of seedlings of native species, resulting in mixed stands with the planted (usually exotic) trees initially dominating the main canopy and naturally regenerating native species being dominant in the understory (Kuusipalo et al., 1995; Otsamo, 2000; cf. Wills et al., 2016). Upon maturation, this kind of forest neither classifies as a traditional plantation forest nor as fully naturally developed secondary forest, hence within the context of tropical forest landscape restoration activities the term 'reforest' has been proposed for these multi-species ecosystems (Chazdon et al., 2016). Where resin- or fruit-producing trees make up a sizeable proportion of the planted mixture, the term 'agroforest' (de Foresta and Michon, 1997; cf. Snelder and Lasco, 2008) is often used.

The Philippines, where *Imperata* and related grasslands (locally referred to as *cogon*) cover as much as 17% of the total land area (~5 million ha; Garrity et al., 1997), launched an ambitious 'National Greening Program' in 2011 targeting tree planting on 1.5 million ha of degraded land (much of it *cogon*) during an initial period of six years (Aquino and Daquio, 2014). According to FAO (2016), the Philippines managed to reforest an impressive 240,000 ha between 2010 and 2015, thereby turning the net loss of forest cover of the previous decades into a net gain and joining China, India and Vietnam as so-called 'forest transition' countries (Meyfroidt and Lambin, 2011). However, indiscriminate large-scale planting of trees for carbon sequestration, combating surface erosion, or improving livelihoods has also attracted considerable criticism, mostly in terms of adverse effects on catchment water yields (Jackson et al., 2005; Trabucco et al., 2008; Cao et al., 2011). At the same time, reports of *improved* dry-season flows after reforesting degraded land have begun to appear in the literature (Zhou et al., 2010; Krishnaswamy et al., 2012; Choi and Kim, 2013, 2015), suggesting that under certain conditions (e.g. advanced land degradation) the higher water use of planted or regenerating trees may be more than compensated by the gradually improving capacity of the soil to accommodate and retain intensive rainfall (the so-called 'infiltration trade-off' hypothesis; Bruijnzeel, 1989, 2004; cf. Chandler, 2006). Surface infiltration capacity increased after reforesting fire-climax grasslands for a 12-year-old teak plantation in Sri Lanka (Mapa, 1995) and 40-year-old mahogany or pine stands in the Philippines (Baconguis and Daño, 1984) but not in the case of *Pinus caribaea* in Fiji, due to inherent soil textural differences between the respective sites (Waterloo, 1994). Snelder (2001a) reported much lower infiltrability for *Imperata* grassland soils in the northern Philippines compared to adjacent forest patches although no significant difference was observed between heavily grazed and regularly burned *cogon*, and lightly grazed and occasionally burned *cogon*. However, none of these studies compared rainfall intensity characteristics with infiltrability or saturated soil hydraulic conductivity (K_{sat}) profiles with depth to infer the prevailing dominant (near-)surface runoff generation mechanisms (cf. Ziegler et al., 2004; Bonell et al., 2010; Ghimire et al., 2014).

As part of a study examining the possible causes of an alleged improvement of dry-season streamflow due to soil improvement after reforesting a degraded *Imperata* grassland area on the island of Leyte (the Philippines) using a space-for-time substitution approach (Walker et al., 2010), we measured key soil physical characteristics of a degraded *Imperata* grassland (Basper site) and a nearby 23-year-old reforest site established on former *cogon* land and underlain by the same rock- and soil type (Manobo site). Evaluation of the changes in soil characteristics associated with plantation maturation or forest regeneration in real time would require a correspondingly long period of periodic re-sampling of the respective sites (Alegre and Cassel, 1996; Yonekura et al., 2010; Zimmermann et al., 2010; Ghimire et al., 2014; cf. discussion in Johnson and Miyanishi, 2008). Hence, for practical reasons most studies have resorted to a space-for-time substitution in which comparable initial conditions are assumed for carefully selected sites (e.g. Ziegler et al., 2004; Zimmermann et al., 2006; Hassler et al., 2011; Zwartendijk et al., 2017). Rock type (gabbro), basic soil type (Eutric Cambisols), slope steepness (20–30°) and aspect (southerly), as well as climate were the same for the Basper grassland and Manobo reforestation sites. The pre-reforestation land use at Manobo (see Sections 2.1 and 4.1) was also similar to that at Basper. These similarities between the two sites suggest that meaningful comparisons can be made (cf. Walker et al., 2010). Measured variables included soil texture and organic carbon content, bulk density and porosity, as well as K_{sat} down to a depth of 100 cm. In addition, rainfall intensity and soil moisture content at different depths were measured continuously to infer potential differences between the two sites in terms of the frequency of occurrence of infiltration-excess (IOF) and saturation-excess overland flow (SOF; Dunne, 1978; cf. Bonell, 2005). Specifically, we hypothesized that: (i) surface K_{sat} associated with the semi-mature reforest would be significantly higher than for the *Imperata* grassland; (ii) surface K_{sat} in the grassland would be low enough for IOF and SOF to occur regularly; and (iii) variation in K_{sat} with depth in the reforest is such that runoff would consist predominantly of lateral subsurface stormflow (SSSF; Elsenbeer, 2001; cf. Bonell, 2005).

2. Materials and methods

2.1. Study area

Two small headwater catchments with contrasting land cover but the same geological substrate (gabbro; Dimantala et al., 2006), soil type (Eutric Cambisols) and similar elevation range and aspect (southerly) were selected near Tacloban City, NE Leyte Island, the Philippines, for comparative soil physical and hillslope hydrological response characterization: (i) Basper (3.20 ha; central coordinates 11°15′ N and 124°57′ E; elevation range: 50–135 m a.s.l) representing a fire-climax grassland and (ii) Manobo (8.75 ha; 11°17′ N, 124°56′ E; 50–240 m a.s.l) representing a ~23-yr old community-managed multi-species reforest. The two sites are ~3.5 km apart. Soils in both locations have a predominantly clay loam texture grading to sandy clay loam below 0.9 m depth (see also Results below). At Basper, the upper slopes are straight to slightly concave while the lower slopes steepen towards the stream; the average slope is ~23°. Landslide scars are prominent (Fig. 1a). The vegetation consists of *cogon* grass (*Imperata cylindrica* L.) on the ridges and upper slope segments, with the grass being mixed with sedges (*Cyperus* sp.) in less well-drained parts; mixed grassland and shrubs (< 1.5 m high; mostly *Melastoma malabathricum* (L.) Smith and *Chromolaena odorata* (L.) R.M. King & H. Robinson) dominate the mid-slope, while shrubs and young trees (2–3 m high; mostly *Neonauclea lanceolata* (Blume) Merr. and *Leukosyke capitella* Wedd.) are common on the lowermost slopes near the streams, along with a few remnant planted *Acacia mangium* Willd trees near the outlet (Fig. 1a). Although regularly burned in the past, the area did not experience any fire after 2003 and was not grazed at the time of the study (2013–2014). Remnants of rudimentary terraces beneath the grasses