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Effects of trees on infiltrability and preferential flow in two contrasting agroecosystems in Central America

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ABSTRACT

We tested the hypothesis that trees have measurable effects on infiltrability, macroporosity, and preferential flows in agrosilvopastoral systems. Managing agricultural systems for water conservation is a critical component of sustainable systems. We investigated the relationship between infiltrability and the distance to the nearest tree, and whether differences in macroporosity can account for differences in infiltrability.

In both systems, preferential soil water flows were dominant compared to matrix flow. Trees in the pasture landscape improved infiltrability and preferential flow but had no significant effect in the coffee agroforestry system. After comparing rainfall intensity and frequency data to the measured infiltrability values, we conclude that trees in the pasture system reduce surface runoff at the highest observed rainfall intensities (>50 mm h^{-1}). The volcanic soils of the coffee plantation are less degraded and their high natural permeability has been maintained. Since the coffee plants at this site are established (40 years) perennial vegetation with substantial residues and extensive root systems like trees, they improve soil physical properties similarly to trees.

Trees increase hydrologic services in pasture lands, a rapidly expanding land use type across Latin America, and therefore may be a viable land management option for mitigating some of the negative environmental impacts associated with land clearing and animal husbandry. However, in land management practices where understorey perennial vegetation makes up a large proportion of the cover, such as for coffee agroforestry systems, the effect of trees on infiltration-related ecosystem services could be less pronounced

1. Introduction

Cattle farming has been the most rapidly-growing land use type in Central America, with the area of land allocated to this purpose increasing by 7 million hectares during the period of 1980–2000 (Gibbs et al., 2010). According to the FAO, there were 85 million hectares of permanent meadows and pasture lands in Central America in 2009, representing 35% of the region's usable land (FAO, 2012). It has been predicted that the establishment of new pastures will be the driving force for 69% of the deforestation that is projected to occur from 2010 onwards in this region (Wassenaar et al., 2007). Because of this expansion of pastures, it has been argued that it will be necessary to transform the means of livestock production in Latin America (Murgueito and Ibrahim, 2001). Methods based around increasing the tree cover provided by conventional grass monocultures could play a central role in this transformation (Murgueitio et al., 2011).

Water quality and quantity are important limiting factors that affect socioeconomic development, human health and environmental sustainability in many regions of the world (Meadows and Meadows, 2007; Meadows et al., 1974). In recent years, the concept of ecosystem services has been used to integrate scientific understanding of biophysical processes with socio-economic analysis. The storage and retention of water, and the regulation of water supplies, have been described as hydrological ecosystem services (HES; Costanza et al., 1997; de Groot et al., 2002).

Facing the rapid expansion of pasturelands across Latin America, we need strategies that can easily be implemented on farms to reduce environmental impacts and improve water quality and quantity in particular, where trees may provide such services, but data are sparse.

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Previous studies on the relationship between trees and water distribution focused primarily on forest plantations (Bruijnzeel, 2004; Scott et al., 2005; van Dijk and Keenan, 2007); the effects of isolated trees or small clusters of trees in livestock farms and agroforestry systems on groundwater recharge have not been studied extensively. However, one recent study in this area found that the level of water infiltration in a coffee agroforestry system was greater than that in a coffee monoculture (Cannavo et al., 2011).

Trees modify the microclimate (Charbonnier et al., 2013) and variables that affect the water balance at the local scale, such as interception, transpiration, infiltration, surface runoff and soil evaporation. Depending on the circumstances, these effects may or may not be beneficial in terms of maintaining adequate ground water recharge rates and dry season flows (Bruijnzeel, 2004). Over the last few years, numerous afforestation and reforestation projects have been initiated with the aim of mitigating the effects of climate change. An underappreciated issue associated with such projects is their potential effects on hydrological ecosystem services, which arise from the trees' high water use reducing downstream water flow (Trabucco et al., 2008). A recent meta-analysis showed that the total flow levels for planted and natural forests are lower than those for non-forest lands (Locatelli and Vignola, 2009). Jackson et al. (2005) reported that tree plantations decreased both annual total and dry season stream flows. However, it has been pointed out that these studies focused exclusively on data for subhumid tropical and temperate areas (Malmer et al., 2010). This is significant because the soil water balance is dependent on soil mineralogy and texture, local rainfall patterns, and tree cover across the landscape. At the local scale, trees affect flow in two main ways. First, they influence the soil's permeability and thus affect positively the soil water infiltration. Second, they increase evapotranspiration because of canopy interception and the uptake of water in the root zone via the roots. There is also evidence that forests affect rainfall patterns at the regional level (Ellison et al., 2012; Makarieva et al., 2013; Makarieva and Gorshkov, 2007). Even over timescales of less than a day, evapotranspiration in the cover can be expected to influence the streamflow (Bond et al., 2002; Cadol et al., 2012).Trees often have deep root systems and produce more residues than other cover types, increasing the soil organic matter content and improving water retention in the top soil. This also increases the soil's porosity and facilitates water infiltration (Ilstedt et al., 2007). While meta-analyses have shown that the introduction of trees into agricultural fields and afforestation in the tropics can both increase infiltrability, quantified by the rate of water infiltrated in the soil until reaching a steady state ratio, in general, Ilstedt et al. (2007) have stressed that the existing data are insufficient to fully understand the precise impacts of such changes at the local level. For example, there may be situations in which trees increase infiltration to a much lesser extent (or do not increase it at all) than would be expected based on the general case. The inherent macroporosity of naturally permeable soils such as those of volcanic origin may be so high that tree roots and litter do not increase it significantly or contribute meaningfully to soil infiltrability. In addition, the understory may also affect infiltration positively or negatively, and depending on its nature (e.g. whether it is deep rooted or not, perennial or not, compacted or not) may also interact with the overstory trees. It is therefore important to characterize different situations in order to determine how trees within the agroecosystem affect the soil water balance. The process of infiltration affects the magnitude and quality of both soil- and ground-water systems (Wu et al., 1996), and is essential for their replenishment and maintenance (Grinevskii and Novoselova, 2011). Infiltration has therefore been studied for a long time, particularly in the context of agriculture (Chapman, 1990). However, there is still a lack of data on infiltration in various soil types found in the tropics, and how it is altered by land management in these regions (Bruijnzeel, 2004; Malmer et al., 2010). Simple hydrological process models often neglect the role of infiltrability and its dependence upon rainfall intensity, but there is an increasing awareness that both processes should be considered simultaneously (Jackson et al., 2005). This is particularly important in the tropics, which have very intense rainfall and where soils are often prone to degradation and compaction. In this region, the comparison of rainfall intensities with infiltrability is of main importance to evaluate the potential effects of these intense rainfalls on runoff generation and soil erosion. It is important to understand how trees affect infiltrability to facilitate the accurate parameterization of hydrological models in order to account for the spatial heterogeneity introduced by the presence of trees in the humid tropics (Ilstedt et al., 2007).

Trees are integral components of many cropping (e.g. coffee, cacao agroforestry) and silvopastoral systems in the tropics (Somarriba et al., 2012). Initiatives aimed at increasing the biodiversity within coffee-producing regions by introducing trees have been widely adopted in Central America, due to environmental concerns, together with low coffee prices (Muschler and Bonnemann, 1997). In addition, soil carbon sequestration and agroforestry are often promoted as management options in small-scale agriculture. This is driven by a multitude of factors, including the need for food security and to mitigate the impact of climate change (DeFries and Rosenzweig, 2010; Verchot et al., 2007).

To determine the role of isolated trees in the agrosilvopastoral systems of Central America, we investigated how trees affect soil infiltrability and macroporosity, which are two of the key variables that govern groundwater recharge. In this work we describe two agroecosystems that were selected to represent two extreme situations in terms of infiltration: an agroforestry-based coffee plantation located in the humid tropical environment of Costa Rica and a pasture landscape with an extended dry season in Honduras. The coffee agroforestry system was located on naturally permeable volcanic soils, and we assumed that the impact of the densely-rooted coffee plants on infiltration would be similar to those of trees. The pasture landscape had a lower level of tree cover, and we assumed that animal trampling would compact and degrade the topsoil. It was hypothesized that in both cases, the soil infiltrability and macroporosity would be influenced by (1) soil type, and (2) land management.

We therefore aimed to test the hypothesis that in agrosilvopastoral systems there is a positive effect of isolated trees on infiltration. Specifically, the aims of our study were to: (1) investigate the effects of isolated trees on infiltrability and preferential flows, and the distance over which these effects apply, (2) compare infiltrability and rainfall intensity, and (3) evaluate the importance of the prevailing conditions (soil type, land use patterns, understory composition).

2. Material and methods

2.1. Locations and sites

The aim of having these two study sites is not as a comparison, but to test the hypothesis that trees have a positive effect on infiltrability in these two systems that are common land uses in the tropics and where the inclusion of trees can have a role in hydrological ecosystem services.

2.1.1. Study site 1: Coffee plantation agroforestry system in Turrialba, Aquiares, Costa Rica

This study was conducted in a coffee agroforest located in the Aquiares farm, herein referred as Aquiares, one of the largest coffee farms in Costa Rica (6.6 km^2) and site of the Coffee-Flux observatory (SOERE F-ORE-T, http://www5.montpellier.inra.fr/ecosols/