Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 117 No. 2 (2016) 309–321

urn:nbn:de:hebis:34-2016101851061 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Throughfall and soil properties in shaded and unshaded coffee plantations and a secondary forest: a case study from Southern Colombia

Lucía Gaitán [a,c,*], Inge Armbrecht [b], Sophie Graefe [a]

[a] *Georg-August-Universität Göttingen, Tropical Silviculture and Forest Ecology, Göttingen, Germany*
[b] *Universidad del Valle, Departamento de Biología, Cali, Colombia*
[c] *International Center for Tropical Agriculture (CIAT), Pham Van Dong, Tu Liem, Hanoi, Vietnam*

Abstract

In Colombia coffee production is facing risks due to an increase in the variability and amount of rainfall, which may alter hydrological cycles and negatively influence yield quality and quantity. Shade trees in coffee plantations, however, are known to produce ecological benefits, such as intercepting rainfall and lowering its velocity, resulting in a reduced net-rainfall and higher water infiltration. In this case study, we measured throughfall and soil hydrological properties in four land use systems in Cauca, Colombia, that differed in stand structural parameters: shaded coffee, unshaded coffee, secondary forest and pasture. We found that throughfall was rather influenced by stand structural characteristics than by rainfall intensity. Lower throughfall was recorded in the shaded coffee compared to the other systems when rain gauges were placed at a distance of 1.0 m to the shade tree. The variability of throughfall was high in the shaded coffee, which was due to different canopy characteristics and irregular arrangements of shade tree species. Shaded coffee and secondary forest resembled each other in soil structural parameters, with an increase in saturated hydraulic conductivity and microporosity, whereas bulk density and macroporosity decreased, compared to the unshaded coffee and pasture. In this context tree-covered systems indicate a stronger resilience towards changing rainfall patterns, especially in mountainous areas where coffee is cultivated.

Keywords: coffee, saturated hydraulic conductivity, precipitation, shade trees, throughfall

1 Introduction

Coffee production systems represent an example of how land-use change produced distinct transformations in the Colombian landscape, a tendency that can be also observed for other coffee producing areas in Latin-America (Perfecto *et al.*, 1997; Armbrecht *et al.*, 2005). Since 1970, coffee farming in Colombia has continuously moved from shade-grown cultivation to low-shade or no-shade cultivation (Cárdenas, 1993; Guhl, 2004), for instance, from 2007 to 2013 the area of unshaded coffee plantations increased from 4200 to 5530 km^2 (FNC, 2014).

Due to its floral complexity coffee that is grown under a shade canopy has a forest-like structure, providing different, albeit neglected benefits to the agroecosystem, including climate regulation, protection from pathogens and insects, improvement of soil fertility, biodiversity conservation and carbon sequestration (Perfecto *et al.*, 1996; Beer *et al.*, 1998; Lin, 2007). Furthermore, it has allowed some farmers to access premium eco-certification programs, to gain additional revenues and to contribute to environmental welfare (Castro *et al.*, 2004; Vaast *et al.*, 2005).

* Corresponding author
Email: lucia.gaitan.sanchez@gmail.com
Phone: +84 1636451524; Fax: +84 125 8159705

Published online: December 9, 2016

Climate projections for Colombia show that temperatures will most likely increase by 2.5 °C and precipitation by 2.5 % by the year 2050. The country is also affected through climate variations related to El Niño and La Niña (Lau *et al.*, 2010), i.e. in the season 2011–2012 La Niña reduced the number of dry months in the Colombian coffee region from four to one (FNC, 2012). There is a strong tendency towards an increase in the variability of precipitation, with the wettest periods becoming wetter and the driest periods becoming less dry (Lau *et al.*, 2010). Such variations in rainfall will alter flowering dates of coffee and the hydrological cycles in the plantations, and will most likely result in yield reductions (Porter & Semenov, 2005; Läderach *et al.*, 2011). Through simulation models Van Oijen *et al.* (2010) found that doubling the amount of rainfall would negatively affect coffee production systems in 28 % of the cases in Central America, whereas at the same time, 50 % higher nitrogen losses and 336 % higher soil losses would occur. Additionally, a 5 °C increase in temperature resulted in a 19 % decrease of coffee yield in unshaded coffee compared to shaded coffee.

Preventing shaded coffee plantations from being converted to monocultures or conversely, introducing shade trees in open plantations may be important strategies to mitigate the effects of extreme rainfall and temperature events, since trees modulate the micro-environment by buffering humidity and soil moisture availability and by enhancing soil organism activity (Martius *et al.*, 2004; Siles *et al.*, 2010b). Furthermore, the Colombian Coffee Growers Federation has a strong interest in developing compensation schemes for hydrological services provided by trees in river basins of the coffee growing region (Sosa & Moreno, 2014).

Depending on the canopy characteristics of vegetation, different amounts of water are intercepted by the canopy and evaporated directly into the atmosphere (Hodnett *et al.*, 1995; Grip *et al.*, 2004). This is also true for shaded vs. unshaded coffee, which differ significantly in the amount of vegetation. Measuring throughfall is an efficient way to determine the amount and distribution of water that reaches the soil (net rainfall) in this context. Throughfall is mainly influenced by the vegetation structure, the intensity and duration of precipitation (Crockford & Richardson, 2000). For instance, light rain with small raindrops will be rather intercepted by the canopy, whereas heavy rains will saturate the upper canopy storage capacity, transmitting most of it to the lower strata (Salas, 1987). Also, the presence of shade trees and other vegetation creates a second layer above the coffee plants, which increases the variability of vertical water distribution and reduces the amount of water reaching the soil (Herwitz, 1985; Siles *et al.*, 2010a). Once rainfall reaches the soil, many factors influence water storage and movement, such as infiltration rate, porosity and texture (Zimmermann *et al.*, 2006; Scheffler *et al.*, 2011). These properties depend on land use type and management practices. Forest cover promotes water infiltration and groundwater recharge during the rainy season, and is able to supply water during the dry season. However, those soil hydrological dynamics of forests are often lost by land conversion (Bruijnzeel, 1989; Sandström, 1998; Malmer *et al.*, 2009). In general, land use practices involving any sort of farming (crop cultivation, grazing) affect the soil physical properties by the decrease of water storage in the soil and a reduction in the movement through the soil profile (Jaramillo, 2002b).

The present study aimed at measuring throughfall and soil hydrological properties in four different land use types in a coffee producing region of South-Western Colombia: shaded coffee, unshaded coffee, secondary forest (positive control) and pasture (negative control). It was assumed that the presence of shade trees in coffee plantations reduces the net rainfall compared to unshaded coffee due to a higher interception loss. Furthermore, shade trees might improve soil hydrodynamics in a way that the net rainfall input in the tree-covered systems will infiltrate and conduct a greater amount of water into the soil profile with a possible runoff reduction.

2 Materials and methods

2.1 *Study sites*

The field study was conducted during the months of highest rainfall, April and May 2013, at “Vereda El Rosal” (02° 51′ 856″ N, 0.76° 33′ 916″ O), which belongs to the district of Mondomo in the municipality of Caldono, department of Cauca. The study sites were located on the eastern slopes of the western Andean mountain range (Cordillera Occidental) at elevations of 1340 to 1430 m a.s.l. The climate is mild and humid, with a mean annual temperature of 22 °C and annual rainfall of 1600 mm (Jaramillo *et al.*, 2011). The rainfall patterns are bimodal with rainfall peaks recorded during the months of April–May and October-November, and a dry period lasting from May to October, which is interrupted by a smaller rainy season in July–August (Pardo-Locarno *et al.*, 2005). The soils are derived from deposits of volcanic ashes over igneous rocks, and are deep and well drained (IGAC, 2009).

Average rainfall registered at the El Madrigal Meteorological Station from 1997 to 2010 was 108 mm for the month of April and 103 mm for the month of May (FNC, 2013). However, during the period of 2006–2013 above average rainfall values were already recorded except for the year 2009, and the year-to-year variability was high (Fig. 1a). The number of rainfall events during the months of April and May was between 9 to 18 days month^{-1}, except for the rather dry year of 2009 (Fig. 1b).

The study was conducted on four plots representing the land use systems shaded coffee, unshaded coffee, secondary forest and pasture. The unshaded coffee was located at a distance of 68 m from the pasture and 258 m from the forest, whereas the shaded coffee was 120 m from the pasture. The experimental plots had a size of approximately 40×30 m, and were located within each patch of land use system. The shaded coffee was planted in 2010 beneath approximately 20 years old shade trees, which were located within the coffee row. It comprised a total area of 2 ha, with spacing of 1.4 m between the coffee rows and 1.2 m within the coffee row, resulting in 5674 coffee plants ha^{-1} (Fig. 2b). Shade trees were mainly composed of leguminous *Inga* species and non-leguminous mango (*Mangifera indica*) trees, which were planted within the coffee rows at spa-

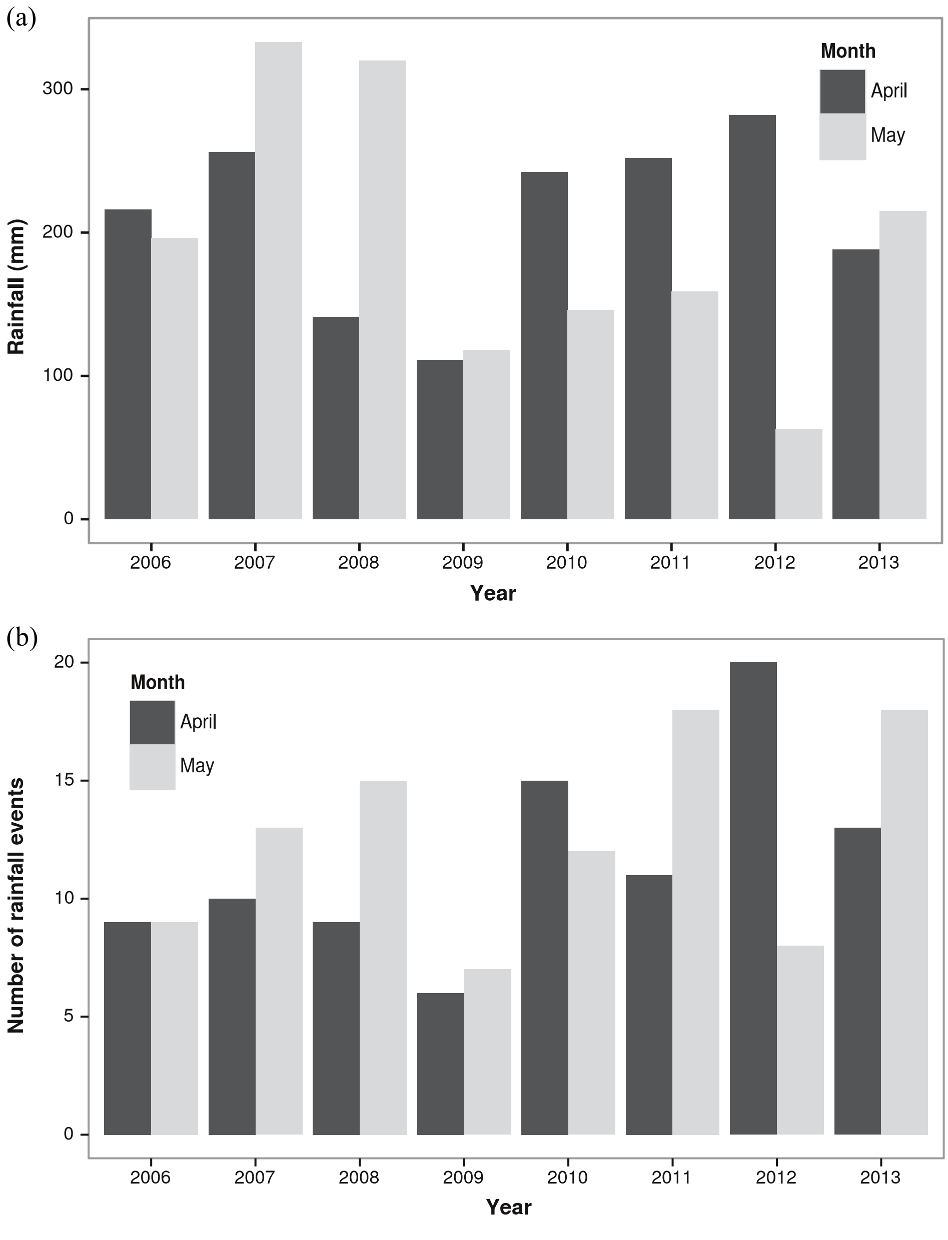

Fig. 1: *(a) Gross precipitation and (b) frequency of rainfall events during the months of April and May. Data from 2006–2012 was taken from El Madrigal Meteorological Station (FNC, 2013), whereas the values of 2013 were obtained in the present study.*

cing of 6×6 to 7×7 m. The unshaded coffee was planted in 2009 and comprised an area of 1 ha, with spacing of 1.5 m between the coffee rows and 1 m within the coffee rows, yielding in a density of 6666 coffee plants ha^{-1} (Fig. 2c; personal communication with farmers 2013). Previously to coffee establishment this plot was a cattle pasture. The area under secondary forest was 4 ha and it existed for at least 14 years. It consisted of a fragment nearby a stream and selective logging was practiced for large diameter trees dominated by the Lauraceae family (personal communication with farmer 2013). The pasture comprised an area of 3 ha. Each hectare was separated and used a rotational grazing system based on 60 days.

2.2 *Throughfall*

In order to determine throughfall, the approach of Siles *et al.* (2010a) was slightly modified (Fig. 2). In each plot nine sets of rain gauges were placed randomly with a minimum distance of 4 m from each other, and at 20 cm height from the ground floor. The rain gauges were made of cylindrical plastic bottles with a diameter of 5 cm, and the volume was standardized through a graduated cylinder. To obtain a temporal comparability throughfall was collected every morning between 7–10AM during two months. Each set consisted of two rain gauges that were placed at distances of 0.1 and 0.5 m from the target plant (Fig. 2a). In the shaded coffee, each of the nine sets comprised two distances from the shade tree (1 m and 2.3 m, Fig. 2b). In this system gauges were placed below four different shade tree species, which were *Inga densiflora* (n=1), *Inga edulis* (n=3), *Mangifera indica* (n=4) and *Oreopanax floribundus* (n=1). In the unshaded coffee and the secondary forest nine sets of rain gauges were placed following the same spacing (Fig. 2c, 2d). In the secondary forest saplings with the same DBH (diameter at breast height) of coffee plants (i.e. 1.9–2.2 cm, in the following called target plant) were chosen, in order to place the rain gauges at the corresponding distances. The distance between the rain gauges and the trees was on average 6.6 m. The same arrangement was followed for the pasture to measure gross precipitation (P_g), i.e. nine sets were placed randomly. To ensure preciseness of the field data P_g was compared to recordings of the Madrigal Meteorological Station located 1.1 km from the study area.

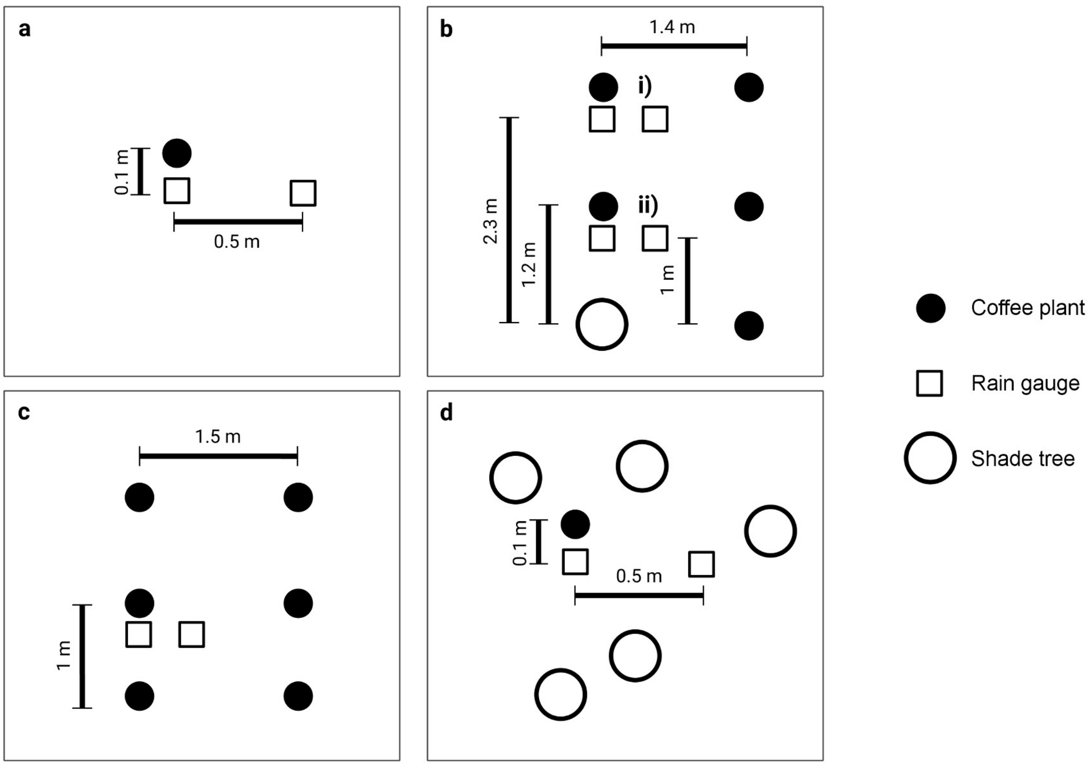

Fig. 2: *Sketch of the experimental design for measuring throughfall in each land use type, based on Siles et al. (2010a). (a) represents one set of rain gauges placed at a defined distance to the coffee plant, (b) set-up in the shaded coffee located at distances of i) 1 m and ii) 2.3 m from the shade tree, (c) set-up in the unshaded coffee, and (d) set-up in the secondary forest, where the sets of rain gauges were placed next to trees with a similar diameter as coffee plants. Since there were no coffee plants or shade trees in the forest, in this case, the black dot represents the target plant referred as to in the text.*

2.3 Stand inventory

In the shaded coffee system, the DBH of the shade trees and the distance to each coffee plant were recorded. In the secondary forest DBH and distance to the rain gauge were recorded for all trees that influenced the set with their canopy. However, all the trees on the plot were counted to calculate stem density. Additionally, the percentage canopy cover was measured for each set with a GRS densitometer in both tree-covered systems. In all four land use types the slope was calculated by measuring the ground level between two points through the steepest part of the slope (FAO, 2013).

2.4 Soil hydrological properties

In order to evaluate major properties determining soil water movement and storage the parameters texture, porosity, bulk density and saturated hydraulic conductivity (K_{sat}) were measured in each land use system. Soil samples were taken to a depth of 30 cm with four replicates from each system. Analyses were performed with established methods (IGAC, 2006) at the Laboratory of Agricultural Soils and Water at the Universidad del Valle in Cali. Soil texture was determined with the Bouyoucos Hydrometer Method. For porosity undisturbed soil samples were taken using a cylinder with a height of 5 cm and a diameter of 5 cm. The samples were weighted at a saturated (M_s), drained (M_d) and dried stage (M_{dry}). Porosity (P_t) was calculated according to the following equation (IGAC, 2006), where V is the volume of the cylinder:

$$\%P_t = \left(\frac{M_s - (M_d + M_{dry})}{V}\right) * 100$$

Bulk density was determined by the core method with the same cylinder. The Porchet method was applied to measure hydraulic conductivity.

2.5 Statistical analysis

R (2.15.3) for Statistical Computing was used to perform statistical analyses. To evaluate the influence of canopy cover and rainfall intensity on the distribution of throughfall a two way analysis of variance was conducted. Given that the assumptions of normality or variance homogeneity were not met for the response variable, a Wilcoxon signed-rank test was conducted. All systems were tested against each other in matched samples. The same was done to assess the effect of land use system on soil parameters.

3 Results

3.1 Stand inventory

All four sites were located on moderately steep (15–30 %) to steep (30–60 %) slopes (Table 1). Compared to the secondary forest, which had 358 trees ha^{-1} with diameters greater than 10 cm, the tree density in the shaded coffee was lower (Table 1). The mean DBH of trees in the secondary forest was significantly lower than the DBH of the shade trees in the coffee system. The percentage canopy cover in the shaded coffee system was high (76 %), but significantly lower than in the secondary forest (92 %, Table 1).

Table 1: *Stand inventory with main characteristics of the four land use systems.*

Land use	*Tree species, genus, familly*	*Mean DBH* (cm)*	*Canopy cover* (%)	*Stem density* (trees ha^{-1})	*Average distance of trees to rain gauge* (m)	*Slope* (%)
Shaded coffee	*Inga edulis* *Inga densiflora* *Mangifera indica* *Oreopanax floribundus*	20.9 ± 2.5 ^{a}	75.7 ± 7.1 ^{a}	278	1.7 ± 0.2 ^{a}	20.1
Secondary forest	*Cupania* sp. *Cinnamomum* sp. Melastomateceae Mimosaseae Lauraceae Myrtaceae	16.0 ± 1.8 ^{b}	92.2 ± 0.9 ^{b}	358	6.6 ± 2.4 ^{a}	43.2
Unshaded coffee	–	–	0	0	–	37.7
Pasture	–	–	0	0	–	31.3

* Only trees with DBH larger than 10 cm were considered

3.2 Rainfall patterns and throughfall

During the two months of the study period rainfall was quite high, with 188 mm in April and 215 mm in May 2013. The amount of water collected as throughfall was strongly influenced by the placement of the rain gauges in all three systems, excluding the pasture (Fig. 1). Significantly lower throughfall was recorded when the rain gauges were placed in the coffee row compared to the coffee inter-row. The same was true for the secondary forest, where the rain gauges were placed at similar distance to the target plants as in the coffee systems (Table 2).

Significantly lower throughfall was measured in the shaded coffee, when rain gauges were placed at a distance of 1 m to the shade tree compared to a distance of 2.3 m to the shade tree, which was due to the higher canopy cover above the coffee at a shorter distance Throughfall and canopy cover, in contrast, had more similar values in the secondary forest at both distances (Tables 1 and 2). In the unshaded coffee system, throughfall was more than twice as high in the coffee inter-row compared to the coffee row (Table 2).

The highest throughfall was recorded in coffee inter-rows in the unshaded coffee system; whereas lowest throughfall was recorded in coffee rows in the shaded coffee at a distance of 1 m to the coffee plant. The variability of throughfall in both coffee systems was higher in the coffee inter-row compared to the coffee row (Table 2).

In the shaded coffee system, significantly higher throughfall was collected below mango trees (*Mangifera indica*) compared to *Inga* spp. For this latter species it was found that throughfall sometimes exceeded P_g (Table 3).

Throughfall was obviously higher in the coffee inter-row than in the coffee row in both the shaded and unshed coffee system for nearly all precipitation ranges, but it did not increase with increasing rainfall intensity. However the spatial variability of throughfall increased with increasing rainfall intensity and increasing distance from the rain gauge to shade trees and coffee plants (Table 4). The secondary forest showed a more similar throughfall distribution between the two rain gauge placements.

3.3 Soil hydrological properties

Soil texture was classified as clay in all four systems. A higher amount of sand minerals was recorded in the shaded coffee and secondary forest, whereas unshaded coffee and pasture had more clay minerals (Table 5). In the shaded coffee and the secondary forest, soil porosity was higher compared to the unshaded coffee and pasture (Table 5). Microporosity dominated all four land use types, indicating higher water storage potential albeit potential problems with drainage and aeration, but pasture and secondary forest showed higher values than the coffee systems. The highest macroporosity was recorded in the shaded coffee and secondary forest. Shaded coffee and secondary forest had also significantly lower bulk densities than the other two systems (Table 5). Highest K_{sat} was found in the secondary forest, followed by shaded coffee and unshaded coffee with significant differences between the tree-covered systems and the pasture. In all four systems K_{sat} was classified as moderately high, except for the secondary forest, which was classified as high (Table 5).

Table 2: *Cumulative throughfall (expressed in % P_g) measured in the coffee row (0.1 m) and coffee inter-row (0.5 m) in the four land use systems. In the shaded coffee throughfall was measured at a distance of 1.0 and 2.3 m from the shade tree.*

Land use		*Coffee row* (%)	*Coffee inter-row* (%)
Shaded coffee	1 m	17.8 ± 4.3 ^{a}	39.9 ± 9.7 ^{a}
	2.3 m	60.3 ± 3.9 ^{b}	80.5 ± 7.2 ^{b}
Unshaded coffee		40.3 ± 3.3 ^{b}	92.9 ± 3.7 ^{b}
Secondary forest *		64.2 ± 3.2 ^{bc}	73.2 ± 3.2 ^{b}
Pasture (control)		100 ± 2.6 ^{c}	100 ± 2.9 ^{b}

Mean values in a column with same letter are not significantly different ($p < 0.05$)
(Mean ± standard error, n = 32)
* The target plants that simulated the coffee plants in the secondary forest were chosen according to the coffee plant DBH

Table 3: *Cumulative throughfall (expressed in % P_g) below the two most common shade tree species. Throughfall was measured in the coffee row (0.1 m) and coffee inter-row (0.5 m) and at two distances from the shade tree (1.0 and 2.3 m).*

Shade tree species	*Distance*	*Coffee row* (%)	*Coffee inter-row* (%)	*Average throughfall* (%)
Inga sp.	1 m	10.6 ± 3.2^{a}	56.2 ± 5.7^{a}	39.1 ± 5.0^{a}
	2.3 m	39.2 ± 18.6^{bc}	50.8 ± 4.7^{a}	
Mangifera indica	1 m	27 ± 9.1^{ac}	72.2 ± 4.7^{ab}	63.1 ± 4.6^{b}
	2.3 m	41.3 ± 11.5^{b}	111.7 ± 15^{b}	

Mean values in a column with same letter are not significantly different ($p<0.05$) (Mean ± standard error, n = 32)

Table 4: *Cumulative throughfall (expressed in % of P_g) grouped into rainfall intensities in the three land use systems. In the shaded coffee throughfall was measured at distances of 1.0 and 2.3 m from the shade tree.*

Rainfall range	*<5 mm*	*5–10 mm*	*10–20 mm*	*20–30 mm*	*>30 mm*
Frequency of rainfall event	11	8	6	4	3
Coffee row (0.1 m)					
Shaded coffee (1 m)	24.8 ± 0.4	7.3 ± 1.1	25.4 ± 1.7	12.6 ± 1.1	20.5 ± 4.0
Shaded coffee (2.3 m)	54.6 ± 0.3	62.5 ± 0.4	66.7 ± 1.8	55.9 ± 2.6	71.6 ± 1.0
Unshaded coffee	46.3 ± 0.3	44.9 ± 0.6	45.0 ± 1.2	51.4 ± 2.1	21.3 ± 2.0
Secondary forest *	59.6 ± 0.3	68.6 ± 0.5	71.8 ± 1.6	60.7 ± 0.1	72.6 ± 3.7
Coffee inter-row (0.5 m)					
Shaded coffee (1 m)	30.4 ± 0.2	41.4 ± 1.6	35.0 ± 2.1	39.5 ± 4.1	14.8 ± 1.4
Shaded coffee (2.3 m)	67.4 ± 0.4	89.6 ± 1.4	96.3 ± 1.6	97.5 ± 6.8	76.9 ± 8.1
Unshaded coffee	94.1 ± 0.5	96.4 ± 1.0	97.3 ± 1.6	87.3 ± 2.8	93.8 ± 5.3
Secondary forest *	64.0 ± 0.3	70.3 ± 0.6	85.8 ± 1.3	75.8 ± 2.3	83.0 ± 2.9

* In the secondary forest rain gauges were placed next to trees with similar DBH as coffee plants (see Fig. 2)

Table 5: *Evaluated soil properties in the four land use systems.*

Soil parameter	*Shaded coffee*	*Unshaded coffee*	*Secondary forest*	*Pasture*
Sand (%)	23.7 ± 0.5^{a}	21.8 ± 5.0^{a}	25.1 ± 2.4^{a}	16.4 ± 2.5^{a}
Clay (%)	66.3 ± 0.5^{a}	61.3 ± 3.9^{ab}	55.8 ± 1.3^{b}	68.3 ± 2.2^{a}
Silt (%)	10 ± 0.8^{a}	17.5 ± 1.3^{a}	19 ± 1.6^{a}	15.2 ± 2.7^{b}
Texture	Clay	Clay	Clay	Clay
Microporosity (%)	46.0 ± 2.54^{ab}	43.4 ± 0.93^{a}	49.1 ± 3.26^{b}	50.0 ± 1.36^{b}
Macroporosity (%)	9.0 ± 4.09^{ab}	6.7 ± 1.95^{a}	7.7 ± 2.89^{a}	2.5 ± 1.08^{b}
Total porosity (%)	55.0 ± 2.5^{a}	50.1 ± 1.3^{b}	56.8 ± 0.78^{a}	52.5 ± 1.08^{b}
Classification of porosity *	Excellent	Satisfactory	Excellent	Satisfactory
Bulk density ($g\,cm^{-3}$)	0.97 ± 0.08^{a}	1.12 ± 0.07^{b}	0.99 ± 0.05^{a}	1.16 ± 0.08^{b}
K_{sat} ($cm\,h^{-1}$)	2.1 ± 0.27^{a}	1.8 ± 0.3^{ab}	3.6 ± 1.5^{a}	1.1 ± 0.27^{b}
Classification of K_{sat} †	Moderately high	Moderately high	High	Moderately high

Mean values in a row with same letter are not significantly different ($p<0.05$) (Mean ± standard error, n = 32)
* According to Kaurichev (1984); † According Soil Survey Division Staff (1993)

4 Discussion

4.1 *Impact of stand structure and rainfall intensity on throughfall*

Throughfall is expected to decrease with increasing leaf area index (LAI) and tree height (Dietz *et al.*, 2006; Siles *et al.*, 2010a). This was reflected in the shaded coffee, which displayed lower throughfall under conditions where rain gauges were placed at a shorter distance to the shade tree. In the shaded coffee a high variability of throughfall was observed, which was not the case for the secondary forest, which can be explained by its natural and randomly distributed stand structure resembling an old-growth forest.

The highest throughfall was recorded in the unshaded coffee when rain gauges were placed in the coffee interrow. The canopy openness of the coffee plants in the unshaded system was higher and displayed larger gaps, which allowed the rain to pass through freely. On the contrary, the presence of trees and the relatively closed canopy in the tree-covered systems intercepted more water, which was also proven by other authors (e.g. Tobón Marin *et al.*, 2000; Park & Cameron, 2008; Siles *et al.*, 2010a). Through the presence of a canopy the velocity of water is reduced, which decreases its kinetic energy and lowers the removal capacity of upper soil layers (Blanco & Lal, 2008). This buffering is of great importance considering the increase of rainfall in this mountainous region. Taking into account the spatial distribution of shade trees in the coffee plantations (on average 6–7 m from each other), coffee plants placed at a closer distance to the shade tree will rather benefit from a higher canopy cover during events of high rainfall. However, a close spacing can also result in competition for water and nutrients between shade trees and coffee plants (Beer *et al.*, 1998). Cannavo *et al.* (2011) found that soil water content was similar between shaded and unshaded coffee in the upper layers, suggesting that shade trees rather use water from deeper soil layers. Their study was conducted in an area where annual rainfall exceeds evapotranspiration, same as in the present study. However, during the dry season evaporation may exceed rainfall for a certain time period, which can limit water availability in the system. Yet better soil properties and a slower drying of the soil due to shaded conditions may compensate the lower net rainfall in shaded coffee systems.

Throughfall values obtained in the present study were comparable to results of Siles *et al.* (2010a) from Costa Rica, who recorded throughfall of 54 % and 94 % in rain gauges placed at distances of 0.1 and 0.5 m to the coffee plant in shaded coffee, as well as 64 % and 97.5 % in unshaded coffee. Dietz *et al.* (2006) reported throughfall of 79 % in a forest with small timber extraction, which could be compared to the secondary forest of the present study, and 82 % in a cacao agroforestry system in Sulawesi, Indonesia. Tobón Marin *et al.* (2000) recorded throughfall of 82 to 87 % in different forest types in the western Amazon. Extremely high throughfall recorded in the shaded coffee can be explained by the concentration of water at a single point. In this case leaves may act as a funnel, and in some rain gauges throughfall was twice as high as P_g. This pattern was also observed by Jaramillo (2003) in coffee shaded with eucalypt, and to a lesser extend in a forest.

It was not possible to measure stemflow in the present study; thus net-rainfall might be underestimated to a certain extent. Trees may benefit from stemflow, which causes a concentration of rainfall near the stems (Schroth *et al.*, 1999). Several authors found stemflow of only 1–3 % of P_g in tropical forest (e.g. Hölscher *et al.*, 2004; Dietz *et al.*, 2006; Macinnis-Ng *et al.*, 2013), while a study conducted by Siles *et al.* (2010a) found 7 % stemflow in a coffee monoculture and 10 % in a shaded coffee system in Costa Rica.

In our study a trend towards a higher throughfall with increasing rainfall intensity was only observed for the secondary forest, and the variation across land use types was high. E.g. rainfall events in the range of 20–30 mm day^{-1} contributed to 12.7 % of throughfall in shaded coffee, but 60.7 % of throughfall in secondary forest. The significantly higher throughfall below *Mangifera indica*, compared to *Inga* spp. can be attributed to its lower extension of branches and a rather smooth surface of the leaves. This points to the fact that structural parameters such as stem density and plant architecture (e.g. structure and arrangement of branches and leaves) have a stronger influence on throughfall than the intensity of rainfall events, which was also found by other authors (e.g. Tobón Marin *et al.*, 2000; Siles *et al.*, 2010a; Bäse *et al.*, 2012).

4.2 *Influence of vegetation cover on soil hydrological properties*

In general, soil hydrological properties followed a similar pattern in the two tree-covered systems and the unshaded systems, respectively. Tree-covered systems allow the movement of water into deeper soil profiles, reducing the possibility of runoff and soil erosion, which is of relevance when extreme rainfall events occur. Both tree-covered systems existed for more than 14 years, and could have a similar influence on soil properties. Similarity might also be attributed by soil composition, since soil texture influences aeration, drainage and water retention (Jaramillo, 2002a). In general, clay content and particle distribution due to its colloidal constitution does not obstruct water movement completely, yet it creates a longer and difficult way for water to run freely (Jiménez & Rodríguez, 2008). This could explain the significantly higher hydraulic conductivity in the secondary forest and shaded coffee compared to pasture, since pasture showed the highest clay and lowest sand content. On the contrary, the higher percentage of sand and lower percentage of clay in the tree-covered systems could account for the faster water movement through the soil. In addition, it has been reported that higher clay content can lead to compaction processes (Jaramillo, 2002a).

Hassler *et al.* (2011) analysed the effect of secondary forest succession on the hydraulic conductivity of a site that was previously covered by pasture in Central Panama. The study reported the recovery of K_{sat} after 12 years of secondary succession and suggested that these forests could provide similar hydrological services as undisturbed forests. The secondary forest site of our study could have reached a similar stage considering its age and the fact that timber extraction is not high.

The unshaded coffee and the pasture showed higher bulk densities and lower porosity compared to the two tree-covered systems, which can be related to soil disturbance and compaction through animals or human activity (Ziegler *et al.*, 2004; Zimmermann *et al.*, 2006), and may limit water infiltration and increase rain splashing (Cannavo *et al.*, 2011). The low macroporosity of the pasture may be an indicator that the soil is packed, and extremely fine pore sizes may hinder roots to penetrate (Benegas *et al.*, 2014). De Moraes *et al.* (2006) reported a reduction of macroporosity and hydraulic conductivity when forest was replaced by pasture over a time span of 30 years in the eastern Amazon, whereas soil moisture increased, promoting frequent saturation. In fact, several authors suggested that lower infiltration rates and K_{sat}, together with increased bulk density, runoff and soil erosion in pastures are consequences of a lack of woody vegetation together with inappropriate tillage methods (Freebairn & Gupta, 1990; Beer, 1987; Cannavo *et al.*, 2011).

Runoff and soil erosion can be even more relevant considering the steep slopes on which the analysed land use systems were located. Sharma *et al.* (2001) reported that agroforestry interventions such as planting trees reduced soil losses by 22 % on slopes in the Himalayas of Nepal. Verbist *et al.* (2010) found significantly lower runoff in forests and shaded coffee plantations than in a coffee monoculture in Sumatra, Indonesia on slopes of 20–30 %.

Furthermore, compensation schemes for hydrological services might also encourage farmers to adopt the use of shade trees. This approach is currently being promoted by the Colombian Coffee Growers Federation, which is part of a strategy for environmental hydric services in river basins through economic incentives, such as tax waivers, to those coffee growers that conserve natural forests and increase incorporation of trees in their coffee crops (Sosa & Moreno, 2014). The vision is that increasing natural vegetation and trees, especially in the higher mountain belts where water springs are born, will protect both soil and water availability for towns and cities located downward in the Andean mountains.

4.3 *Stand structural characteristics of shaded coffee and secondary forest*

The secondary forest canopy cover in the present study was quite similar or even higher to canopy covers obtained from other studies that were conducted in undisturbed tropical forests, e.g. 90 % in Sulawesi, Indonesia (Dietz *et al.*, 2007) and 83–89 % in the western Amazon (Tobón Marin *et al.*, 2000). Different studies indicate that during secondary succession many forest functions such as canopy closure (but not canopy species composition) approach values of primary forests in a time scale of 5 to 20 years (e.g. Finegan, 1996; Guariguata & Ostertag, 2001) and thus resemble a near natural vegetation. Usually agroforests have a lower canopy cover compared to natural forests or forests with a certain amount of timber extraction, which was also confirmed by Dietz *et al.* (2007). The high variability of canopy cover in the shaded coffee can be related to its stand structural characteristics, i.e. different DBH classes of shade trees, a lower density and variable distances between the shade trees and coffee plants.

The lower DBH of trees in the secondary forest compared to shade trees in the shaded coffee could indicate timber extraction activities in the area. Even though the site seemed quite undisturbed, some farmers stated that timber is used sporadically for furniture and firewood purposes (personal communication with farmer, 2013). In contrast, shade trees in the coffee system, such as mango, citrics, avocado and guamo (*Inga edulis*, *Inga densiflora*) remained for over 20 years since their fruits are used for local consumption.

5 Conclusion

Our case study showed that throughfall was rather influenced by stand structural characteristics than by rainfall intensity. On average throughfall was lower in shaded coffee compared to unshaded coffee and secondary forest, despite of the latter displaying a higher stem density and canopy cover. Tree-covered systems resembled in soil hydrology properties, and showed a better porosity and saturated hydraulic conductivity than unshaded coffee and pasture. In the face of climate change, coffee systems without shade trees could become severely affected by an increase in volume and frequency of rainfall, which can trigger erosive processes and landslides. The use of shade trees will help to reduce runoff and probably also erosion when heavy rainfall occurs. Furthermore, where unshaded coffee exists, a proper conversion and arrangement to shaded coffee could lead to a sustainable production system, with the provision of ecosystem services, and economic incentives to coffee growers through compensation schemes for hydrological services.

Acknowledgements

The Konrad Krieger-Stiftung and the Internationalization program of the Faculty of Forest Sciences and Forest Ecology at the Georg-August-Universität Göttingen provided funding for this study. We are grateful for the support of Dr. James Montoya Lerma, Aldemar Reyes and the students of the Entomology department at the Universidad del Valle in Cali, who helped during project development. Meldy Morales and Catherine Gomez from the Laboratory of Agricultural Soils and Water at Universidad del Valle performed the analyses of soil hydrological properties. We further thank the people from the village El Rosal, especially Doña Martha Paz, for their hospitality and support, as well as the field assistants Maria Ximena Urrutía, Joan Manuel Gaitán and Viviana Alarcón, without whom it would not have been possible to carry out this study.

References

Armbrecht, I., Rivera, L. & Perfecto, I. (2005). Reduced diversity and complexity in the leaf litter ant assemblage of Colombian coffee plantations. *Conservation Biology*, 19 (3), 897–907.

Bäse, F., Elsenbeer, H., Neill, C. & Krusche, A. V. (2012). Differences in throughfall and net precipitation between soybean and transitional tropical forest in the southern Amazon, Brazil. *Agriculture, Ecosystems & Environment*, 159, 19–28.

Beer, J. (1987). Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. *Agroforestry Systems*, 5 (1), 3–13.

Beer, J., Muschler, R., Kass, D. & Somarriba, E. (1998). Shade management in coffee and cacao plantations. *In:* Nair, P. K. R. & Latt, C. R. (eds.), *Directions in Tropical Agroforestry Research*. pp. 139–164, Springer, The Netherlands.

Benegas, L., Ilstedt, U., Roupsard, O., Jones, J. & Malmer, A. (2014). Effects of trees on infiltrability and preferential flow in two contrasting agroecosystems in Central America. *Agriculture Ecosystems & Environment*, 183, 185–196.

Blanco, H. & Lal, R. (2008). Agroforestry. *In:* Blanco, H. & Lal, R. (eds.), *Principles of soil conservation and management*. pp. 259–283, Springer, The Netherlands.

Bruijnzeel, L. A. (1989). (De)forestation and dry season flow in the tropics: a closer look. *Journal of Tropical Forest Science*, 1 (3), 145–161.

Cannavo, P., Sansoulet, J., Harmand, J. M., Siles, P., Dreyer, E. & Vaast, P. (2011). Agroforestry associating coffee and Inga densiflora results in complementarity for water uptake and decreases deep drainage in Costa Rica. *Agriculture Ecosystems & Environment*, 140 (1), 1–13.

Cárdenas, J. (1993). La Industria del café en Colombia. *Ensayos sobre Economía Cafetera*, 6 (9), 3–15.

Castro, F., Montes, E. & Raine, M. (2004). Centroamérica La Crisis Cafetalera: Efectos y Estragias para Hacerle Frente. The World Bank, Latin America and Caribbean Region. Environmentally and Socially Sustainable Development Department (LCSES). Sustainable Development Working Paper 23.

Crockford, R. H. & Richardson, D. P. (2000). Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes*, 14 (16–17), 2903—2920.

De Moraes, J., Schuler, A., Dunne, T., Figueiredo, R. & Victoria, R. (2006). Water storage and runoff processes in plinthic soils under forest and pasture in Eastern Amazonia. *Hydrological Processes*, 20 (12), 2509–2526.

Dietz, J., Hölscher, D. & Leuschner, C. (2006). Rainfall partitioning in relation to forest structure in differently managed montane forest stands in Central Sulawesi, Indonesia. *Forest Ecology and Managament*, 237 (1), 170–178.

Dietz, J., Hölscher, D., Leuschner, C., Malik, A. & Amir, M. A. (2007). Forest structure as influenced by different types of community forestry in a lower montane rainforest of Central Sulawesi, Indonesia. *In:* Tscharnkte, T., Leuschner, C., Zeller, M., Guhardja, E. & Bidin, A. (eds.), *Stability of Tropical Rainforest Margins*. pp. 131–146, Springer, Heidelberg.

FAO (2013). Chapter 4: Measuring vertical angles and slopes. FAO Training Series: Simple methods for aquaculture, Volume 16, 2: Topographical surveys. URL `ftp://ftp.fao.org/fi/cdrom/fao_training/FAO_Training/General/x6707e/x6707e04.htm` (last accessed: 23.09.2015).

Finegan, B. (1996). Pattern and process in neotropical secondary rain forests: the first 100 years of succession. *Trends in Ecology & Evolution*, 11 (3), 119–124.

FNC (2012). Comportamiento de la Industria Cafetera Colombiana 2012. Informes de Gestión. Federación Nacional de Cafeteros de Colombia (FNC). URL `http://www.federaciondecafeteros.org/particulares/es/quienes_somos/publicaciones/` (last accessed: 23.09.2015).

FNC (2013). Anuario Metereológico Cafetero 2006–2012. Federación Nacional de Cafeteros de Colombia (FNC), Cenicafe, Colombia.

FNC (2014). Área cultivada según exposición solar por departamento. Cultivos de café en Colombia. Federación Nacional de Cafeteros de Colombia (FNC). URL `http://www.federaciondecafeteros.org/particulares/es/quienes_somos/119_estadisticas_historicas/` (last accessed: 23.09.2015).

Freebairn, D. M. & Gupta, S. C. (1990). Microrelief, rainfall and cover effects on infiltration. *Soil & Tillage Research*, 16 (3), 307–327.

Grip, H., Fritsch, J. M. & Bruijnzeel, L. A. (2004). Soil and water impacts during forest conversion and stabilization of new land use. *In:* Bonnell, M. & Bruijnzeel, L. A. (eds.), *Forests, Water and People in the Humid Tropics*. pp. 561—589, Cambridge University Press, Cambridge.

Guariguata, M. R. & Ostertag, R. (2001). Neotropical secondary forest succession: changes in structural and functional characteristics. *Forest Ecology and Managament*, 148 (1), 185–206.

Guhl, A. (2004). Café y cambio de paisaje en la zona cafetera colombiana, 1970–1997. *Cenicafé*, 55 (1), 29–44.

Hassler, S. K., Zimmermann, B., Van Breugel, M., Hall, J. S. & Elsenbeer, H. (2011). Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. *Forest Ecology and Managament*, 261 (10), 1634–1642.

Herwitz, S. R. (1985). Interception storage of tropical rainforest canopy trees. *Journal of Hydrology*, 77, 237–252.

Hodnett, M. G., Pimentel da Silva, L., da Rocha, H. R. & Cruz Senna, R. (1995). Seasonal soil water storage changes beneath central Amazonian rainforest and pasture. *Journal of Hydrology*, 170, 233–254.

Hölscher, D., Köhler, L., van Dijk, A. I. J. M. & Bruijnzeel, L. A. (2004). The importance of epiphytes to total rainfall interception by a tropical montane rain forest in Costa Rica. *Journal of Hydrology*, 292 (1), 308–322.

IGAC (2006). Métodos analíticos del Laboratorio de Suelos. Instituto Geográfico Agustín Codazzi (IGAC), Bogotá.

IGAC (2009). Estudio general de suelos y zonificación de tierras del departamento del Cauca a escala 1:100.000. Instituto Geográfico Agustín Codazzi (IGAC), Bogotá.

Jaramillo, Á. (2003). La lluvia y el transporte de nutrimentos dentro de ecosistemas de bosque y cafetales. *Cenicafé*, 54 (2), 134—144.

Jaramillo, Á., Ramírez, V. H. & Pulgarín, J. A. (2011). Patrones de distribución de la lluvia en la zona cafetera. *Avances Técnicos Cenicafé*, 410, 1–12.

Jaramillo, D. F. (2002a). La textura del suelo. *In:* Jaramillo, D. F. (ed.), *Introducción a la ciencia del suelo*. pp. 163–179, Universidad Nacional de Colombia Facultad de Ciencias, Medellín, Colombia.

Jaramillo, D. F. (2002b). Manejo del medio físico del suelo. *In:* Jaramillo, D. F. (ed.), *Introducción a la ciencia del suelo*. pp. 255–294, Universidad Nacional de Colombia Facultad de Ciencias, Medellín, Colombia.

Jiménez, I. & Rodríguez, L. (2008). Diagnóstico de la infiltración y permebailidad en los suelos de la zona de recarga del acuifero Morroa en el area Sincelejo, Corozal y Morroa. Facultad de Ingenieria, Universidad de Sucre, Sincelejo (Sucre), Colombia. pp. 151.

Kaurichev, I. S. (1984). *Prácticas de edafología*. Mir, Moscow.

Läderach, P., Lundy, M., Jarvis, A., Ramírez, J., Pérez, P., Schepp, E. & Eitzinger, K. A. (2011). Predicted impact of climate change on coffee supply chains. *In:* Leal Filho, W. (ed.), *The economic, social and political elements of climate change*. ch. 42, pp. 703—724, Springer, Berlin.

Lau, C., Jarvis, A. & Ramírez, J. (2010). Colombian agriculture: Adapting to climate change. CIAT Policy Brief no. 1. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

Lin, B. B. (2007). Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. *Agricultural and Forest Meteorology*, 144 (1), 85–94.

Macinnis-Ng, C. M. O., Flores, E. E., Müller, H. & Schwendenmann, L. (2013). Throughfall and stemflow vary seasonally in different land-use types in a lower montane tropical region of Panama. *Hydrological Processes*, 28 (4), 2174–2184.

Malmer, A., Murdiyarso, D., Bruijnzeel, L. A. & Ilstedt, U. (2009). Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations. *Global Change Biology*, 16 (2), 599–604.

Martius, C., Höfer, H., Garcia, M., Römbke, J., Förster, B. & Hanagarth, W. (2004). Microclimate in agroforestry systems in central Amazonia: does canopy closure matter to soil organisms? *Agroforestry Systems*, 60 (3), 291–304.

Pardo-Locarno, L. C., Montoya-Lerma, J., Bellotti, A. C. & Van Schoonhoven, A. (2005). Structure and composition of the white grub complex (Coleoptera: Scarabaeidae) in agroecological systems of northern Cauca, Colombia. *Florida Entomologist*, 88 (4), 355–363.

Park, A. & Cameron, J. (2008). The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a Panamanian plantation. *Forest Ecology and Managament*, 255 (5), 1915–1925.

Perfecto, I., Rice, A. R., Greenberg, R. & Van der Voort, M. E. (1996). Shade coffee: A disappearing refuge for biodiversity. *BioScience*, 46 (8), 598–608.

Perfecto, I., Vandermeer, J., Hanson, P. & Cartin, V. (1997). Arthropod diversity loss and the transformation of a tropical agroecosystem. *Biodiversity and Conservation*, 6 (7), 935–945.

Porter, J. R. & Semenov, M. A. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360 (1463), 2021–2035.

Salas, G. (1987). Suelos y ecosistemas forestales; con énfasis en América Tropical. Turrialba, IICA.450.

Sandström, K. (1998). Can forests 'provide' water: widespread myth or scientific reality? *Ambio*, 27 (2), 132–138.

Scheffler, R., Neill, C., Krusche, A. V. & H. Elsenbeer, H. (2011). Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier. *Agriculture Ecosystems & Environment*, 144 (1), 281—289.

Schroth, G., da Silva, L. F., Wolf, M.-A., Teixeira, W. G. & Zech, W. (1999). Distribution of throughfall and stemflow in multi-strata agroforestry, perennial monoculture, fallow and primary forest in central Amazonia, Brazil. *Hydrological Processes*, 13, 1423–1436.

Sharma, E., Rai, S. C. & Sharma, R. (2001). Soil, water and nutrient conservation in mountain farming systems: Case-study from the Sikkim Himalaya. *Journal of Environmental Management*, 61 (2), 123—135.

Siles, P., Vaast, P., Dreyer, E. & Hermand, J. M. (2010a). Rainfall partitioning into throughfall, stemflow and interception loss in a coffee (*Coffea arabica* L.) monoculture compared to an agroforestry system with *Inga densiflora*. *Journal of Hydrology*, 395 (1), 39–48.

Siles, P., Vaast, P. & Harmand, J. M. (2010b). Effects of Inga densiflora on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. *Agroforestry Systems*, 78 (3), 269–286.

Soil Survey Division Staff (1993). Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture. Handbook 18.

Sosa, C. & Moreno, C. (2014). Esquema de compensación por servicios ambientales hídricos en el sector productivo cafetero. Caso microcuenca Toro, Valle del Cauca. FNC, Cali.

Tobón Marin, C., Bouten, W. & Sevink, J. (2000). Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazonia. *Journal of Hydrology*, 237 (1), 40—57.

Vaast, P., Beer, J., Harvey, C. & Harmand, J. M. (2005). Environmental services of coffee agroforestry systems in Central America: a promising potential to improve the livelihoods of coffee farmers' communities. *In:* Wallace, H. (ed.), *Intregrated management of environmental services in human–dominated tropical landscapes: Inter-American Scientific 4th Conference Series*. pp. 35—39, CATIE, Turrialba.

Van Oijen, M., Dauzat, J., Harmand, J. M., Lawson, G. & Vaast, P. (2010). Coffee agroforestry systems in Central America: II. Development of a simple process-based model and preliminary results. *Agroforestry Systems*, 80 (3), 361–378.

Verbist, B., Poesen, J., van Noordwijk, M., Widianto, Suprayogo, D., Agus, F. & Deckers, J. (2010). Factors affecting soil loss at plot scale and sediment yield at catchment scale in a tropical volcanic agroforestry landscape. *CATENA*, 80 (1), 34–46.

Ziegler, A. D., Giambelluca, T. W., Tran, L. T., Vana, T. T., Nullet, M. A., Fox, J., Viene, T. D., Pinthongf, J., Maxwell, J. F. & Evetth, S. (2004). Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. *Journal of Hydrology*, 287 (1), 124–146.

Zimmermann, B., Elsenbeer, H. & De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: implications for runoff generation. *Forest Ecology and Managament*, 222 (1), 29—38.