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Reciprocal effects of soil moisture dynamics and land-use systems with cacao in Alto Beni, Bolivia

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Abstract

Soil moisture is a function of topography, soil texture, vegetation and meteorological conditions and therefore highly spatial and temporal variable. Vegetation reduces evaporation from the soil but takes up water for production and transpiration. Vice versa, vegetation is affected by water availability. In many agricultural systems, especially in the tropics with distinct dry seasons, water availability limits production. Cacao production relies on a stable humid and warm climate. Drought causes a reduction in yield and long-term drought affects the vitality of the trees. Land-use systems with cacao range from monocultures to highly diverse agroforestry systems. Agroforestry systems have higher water needs for the dense vegetation than monocultures, but little information is available on belowground complementarity or competition for water.

We measured pedohydrological characteristics and soil moisture dynamics in four depths over a 30-months period in six different land-use systems, comprising cacao monocultures, cacao agroforestry systems and a fallow without cacao in a long-term trial in Bolivia. By excluding the influence of topography and soil texture, we could relate the spatial variability to the land-use system. Soil moisture was reduced in the upper 30 cm, implying less plant available water in the main cacao rooting zone in monocultures compared to agroforestry systems. In turn, agroforestry systems exploited water deeper along the soil profile, indicating a complementarity in water use between the cacao and the shade trees. On the other hand, soil texture and water retention capacity influenced the plant available water. In our case, the cacao yield of the same type of production system was not affected by the soil heterogeneity.

Additionally, we assessed the soil moisture and plant available water in a natural regrowth (fallow) of the same age as the cacao plantations. The regrowth had a high naturally developed stem density and a high canopy with low canopy openness. Soil moisture was lower over the whole profile than in the cacao production system, indicating a high water use of the fast growing pioneer species which dominated the stand in comparison to the slow growing cacao and to the multipurpose tree species in the agroforestry systems.

Keywords: soil moisture; water retention capacity; cacao; land-use systems

Introduction

Soil moisture in a landscape it is determined by topography, soil texture, vegetation and meteorological conditions (Mittelbach and Seneviratne, 2012). While the relations of topography, weather and soil texture with soil moisture are mainly unidirectional, vegetation is not only affecting soil moisture content by uptake for transpiration, but also plant available water, a function of soil moisture in relation to pedohydrological characteristics (Siles et al., 2010) determines plant growth. These reciprocal interactions are of major interest when water availability for crops production is limited (Huth and Poulton, 2007). Complex interactions between vegetation and soil moisture are enhanced in mixed cropping systems with different water needs and uptake characteristics.

The cacao tree (*Theobroma cacao* L.) relies on a humid and warm climate. Dry spells as well as water logging can be critical for cacao production (Schwendenmann et al., 2010), therefore soils should be well drained to avoid logging and have a good retention capacity to maintain soil moisture during the dry season (Alvim, 1960). Prediction for climatic changes in cacao producing regions include an increase in temperature that will increase the water needs of the trees by enhanced transpiration (Lin, 2010) and variation in the distribution of precipitation over the year, i.e., drier conditions in the dry season (Läderach et al., 2013). Cacao cultivation ranges from full-sun monocultures to highly diverse agroforestry systems (Schroth et al., 2004). Agroforestry systems compared to monocultures have the potential to reduce stress full conditions by buffering high temperatures and lowering the evapotranspirative demand of the air at the cacao stratum (Niether et al., submitted) and increase the water-use-ratio of the shaded crop, improve infiltration and reduce drainage (Ong and Swallow, 2003). On the other hand, agroforestry systems have a high stem density and primary production that implies a higher water use by increased transpiration (Ong and Swallow, 2003) than a monoculture. Information on belowground interactions in cacao agroforestry systems is contradictory: tree species might compete for the same soil resources (Schroth, 1999) or use the water complementary by different rooting depth (Ong et al., 1991). Cover crops may have a similar effect on the soil water resources as they reduce evaporation from the soil (Schroth et al., 2001) but also consume water by transpiration.

In this study we describe soil moisture dynamics under six different land-use systems, comprising cacao monocultures and cacao agroforestry systems, and a natural fallow of the same age. Monocultures and agroforestry systems were both under conventional and organic management, the latter including a leguminous cover crop (*Neonotonia wightii* (Wight & Ar.) J.A. Lackey; Schneider et al., 2017). While topography and meteorological conditions were the same on the land-use systems, soil texture varied over the trial area (Niether et al., 2017). We exclude the influence of pedohydrological conditions by grouping soil characteristics. Therefore we were able to compare the effect of the land-use systems on the soil moisture. To determine the vice versa effect of soil moisture on vegetation, we compared the performance of cacao trees, i.e., bean production and tree growth, in the same production systems but with two different soil characteristics (Niether et al., 2017).

Materials and methods

Study area and experimental design

All measurements were conducted at the study site Sara Ana in the region Alto Beni at the foothills of the Bolivian Andes. The trial is located on an alluvial terrace at 380 m above sea level with 25.2 °C mean temperature and 83.0% mean relative humidity. 78% of 1440 mm annual precipitation falls in the rainy season from October to April (Niether et al., 2017). The experimental plots were established by the Research Institute of Organic Agriculture (FiBL) in 2008 following a complete randomized design with four replications with a total size of 6 ha. The land-use systems comprised full-sun cacao monocultures (MONO) and cacao agroforestry systems with plantains and woody shade trees (AF), both under conventional (CONV) management and organic (ORG) management including a perennial soybean as a cover crop, a highly diverse successional agroforestry system (SAFS) and a fallow without cropping as a natural control (BAR). Plot size was 48 by 48 m while sampling was conducted in the net-plot of 24 by 24 m. Data were collected in three replications. Further details on the systems and a map of the experimental trial are provided by (Schneider et al., 2017).

Soils and pedohydrological characteristics

Soils of the region Alto Beni are classified as Luvisols and Lixisols (Schneider et al., 2017) with a clay-enriched subsoil (Niether et al., 2017) that causes heterogeneous water retention properties on horizontal and vertical scale influencing the water availability for the plants. Two soil groups (hereafter called ‘A’ and ‘B’) were determined over the trial area and down to 70 cm depth according to their texture, bulk density and moisture retention capacity (pF-curve). Soil group ‘B’ had higher clay and sand content and a higher bulk density, while silt content and porosity were higher in soil group ‘A’. Soil moisture at wilting point and field capacity were lower in soils of the group ‘B’ while the available water content was higher than in ‘A’ (Niether et al., 2017).

Soil moisture measurements

Volumetric water content was measured with a TDR-probe (Trime-Pico IPH/T3, Imko, Germany) equipped with a data-reader (HD2, Imko, Germany) at four depth (10, 30, 50 and 70 cm depth) in tubes that were previously installed along V-shaped transects of 52 m within the net-plots. A total of 41 soil moisture measurement events were conducted over a 30-month period from July 2014 to December 2016. Relative extractable water (REW, which is plant available water) was calculated from soil moisture readings according to Siles et al. (2010):

$$REW = \left(\frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}}\right)$$

where θ is the actual soil volumetric water content, θ_{wp} is the soil volumetric water content at wilting point and θ_{fc} is the soil volumetric water content at field capacity.

Influence of land-use systems on soil moisture and of soil group on cacao performance

Mean REW and variability of REW over the sampling sites and the time was calculated by spatial and temporal statistics, i.e. temporal mean, temporal variance, spatial variance (Mittelbach and Seneviratne, 2012). The mean and variability of the soil groups 'A' and 'B' were calculated and the temporal mean also separated for the land-use systems according to each soil group.

The annual fresh bean yield of the year 2015 and the basal area at 30 cm were compared for cacao trees growing on soil group 'A' and 'B' corresponding to the same production system, i.e. MONO ORG and AF, respectively.

Data analyses

We used R (R Core Team, 2016) to perform linear mixed-effects analysis to describe temporal and spatial statistics of REW in depth across separately for the two soil groups (33 sampling sites for 'A' and 11 sampling sites for 'B'), and for the land-use systems separated for soil groups. When differences were observed, post-hoc analysis of pairwise comparison was performed with differences of least significant means. A Student's *t*-test was used for pairwise comparison of the influence of soil group on yield and stem basal area in one cacao production system.

Results and discussions

Soil moisture dynamics

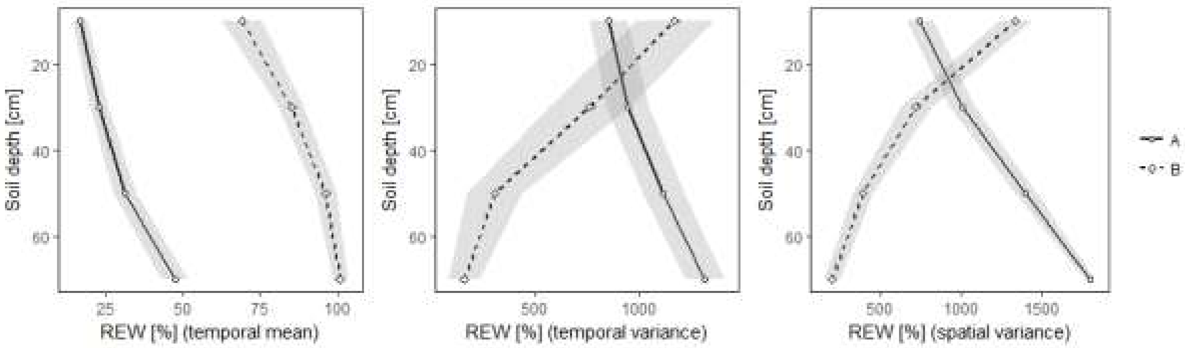

Fig. 1 Relative extractable soil moisture (REW) for the soil groups 'A' (solid line) and 'B' (dashed line) from 10 to 70 cm depth; (a) temporal mean, (b) temporal variance, (c) spatial variance; the shaded area indicates the standard error of the mean.

Over the relatively small area of 4 ha were the measurements were conducted, pedohydrological characteristics were heterogeneous and affected the spatial and temporal dynamics of REW (Niether et al., 2017).The temporal mean REW was generally higher in soils of group 'B' than 'A' and increased in depth (Fig. 1a). The temporal (Fig. 1b) and spatial variances (Fig. 1c) over the measurement period and time were higher in the topsoil in group 'B' than in 'A', showing the influence from seasonality and rain events in the uppermost soil layer. In 'B', the variances decreased drastically in depth with an increase in the clay content, while the variances increased in 'A', were clay content did not increase in depth as in 'B' (Niether et al., 2017).

Influence of land-use systems on soil moisture dynamics

Table 1 Temporal mean and temporal variance of relative extractable water (REW) for the land-use systems separated for the soil groups and depths (mean ± standard error) and results from the linear mixed-effect models.

soil group 'A'		MONO CONV	MONO ORG		AF ORG	SAFS	BAR
temporal	10 cm	25 ±9	19 ±5		22 ±6	13 ±5	10 ±2
mean	30 cm	25 ±8	24 ±5		29 ±5	23 ±8	16 ±4
REW [%]	50 cm	37 ±5	44 ±13		29 ±8	30 ±10	23 ±7
	70 cm	55 ±12	63 ±10		40 ±6	49 ±10	39 ±10
fixed factors						F-value	p-value
Depth						27.8	<0.001
land-use system						1.0	0.414
depth:land-use system						0.7	0.751
soil group 'B'			MONO ORG	AF CONV			

temporal	10 cm	63	±8	79	±11		
mean	30 cm	80	±5	94	±3		
REW [%]	50 cm	101	±2	89	±7		
	70 cm	105	±1	94	±5		
fixed factors						F-value	p-value
depth						9.5	<0.001
land-use system						0.1	0.775
depth:land-use system						3.63.6	0.026

Cacao trees have a tap root growing downwards until 1.5 m, while lateral roots are mainly concentrated in the uppermost 30 cm (Kummerow et al., 1982). In monocultures with only cacao trees, water was mainly reduced in the top soil layers. In MONO CONV and MONO ORG, the temporal mean REW was lowest in the uppermost soil layers and increased from 40 cm to 60 and 80 cm soil depth for both soil groups (Table 1). REW in the top soil layer was similar in AF ORG and the monocultures but the increase of REW with depth was only slightly and REW remained lower in 70 cm depth than in MONO. Especially in soil group ‘B’, REW was higher in AF ORG than in MONO ORG in the top soil layers and remained almost constant over the profile (Niether et al., 2017). The differences between REW in MONO and AF over the profile were even more pronounced when comparing measurement events during the dry season (Niether et al., 2017). Additionally, cacao trees in MONO are exposed to direct sun, higher temperature and higher vapor pressure deficits (Niether et al., submitted) that is directly coupled to higher transpiration (Lin, 2010). Significant lower soil moisture in the upper most soil layer in the dry season in MONO than in than AF indicated that these cacao trees are more likely exposed to drought (Niether et al., 2017).

Differences in REW in the top soil layer between MONO CONV and MONO ORG were not observed indicating that the effect of the soil cover crop was equilibrated between reducing soil evaporation and the own transpiration (Niether et al., 2017).

AF CONV and AF ORG are characterized by a higher stem density, leaf area index and stratification compared to MONO CONV and MONO ORG that imply a higher system transpiration and total water use (Niether et al., 2017). On the other hand, shade trees affect the water use rates of the cacao trees (Köhler et al., 2010), since they are less exposed to high temperatures and evapotranspiration (Niether *et al.*, submitted) thus lowering the water demand (Monteith et al., 1991). Further, the more constant soil moisture over the measured depth indicate, that the associated shade trees exploit water from below the cacao with a deeper rooting system, indicating a complementary water use rather than a competition for water (Niether et al., 2017), as also shown for agroforestry systems with cacao (Schwendenmann et al., 2010) and coffee (Siles et al., 2010).

In contrast to the constant water exploitation over the profile in AF, soil moisture was even lower in the uppermost soil layers in SAFS than in MONO and increased in depth (Table 1), indicating lower rooting depths of the trees in SAFS than in AF. The high density of trees with a lower diameter and the lower stem diameter of the cacao than in the other cacao production systems (Niether et al., submitted) also imply more competition for soil resources between the cacao trees and the shade trees (Niether et al., 2017).

Lower values of REW than in the cacao production systems were observed across all depths in the natural fallow BAR (Table 1) that was related to the natural occurring species water use characteristics (Niether et al., 2017).

No effect of heterogeneous soil and soil moisture conditions on cacao performances

Table 2 Yield and stem basal area of cacao trees (mean ± standard error) in 2015 for the two soil groups ‘A’ and ‘B’ separated for the production systems MONO ORG and AF (including AF ORG in ’A’ and AF CONV in ‘B’) and results from the student’s t-test (Niether et al., 2017).

MONO ORG	‚A‘		‚B‘		t-value	p-value
stem basal area [cm^2]	170	±18	139	±10	1.5	0.182
yield [kg fresh bean $tree^{-1}$ $year^{-1}$]	5.4	±0.5	4.6	±0.5	1.1	0.301
AF						

stem basal area [cm^2]	99	±11	95	±3	0.4	0.714
yield [kg fresh bean $tree^{-1}$ $year^{-1}$]	4.1	±0.6	3.7	±1.2	0.3	0.786

While the production system has a clear influence on cacao growth and production (Schneider et al., 2017), also drought has a negative impact on yield (Schwendenmann et al., 2010). We did not observe differences between the basal area and the yield from cacao trees growing on soils from group ‘A’ and ‘B’, neither for cacao trees in MONO ORG nor in AF (Table 2). Soils from group ‘B’ had higher REW through the year (Fig. 1), but also in soils from group ‘A’ relative extractable water did not decrease below wilting point over the measurement period (Niether et al., 2017). However, if rainfall patterns change as predicted in Alto Beni (Niether et al., submitted), it is possible that REW will decrease below the wilting point during the dry seasons and induce water deficit for the cacao growing in production systems related to soil group ‘A’ (Niether et al., 2017).

Conclusions

We found complementarities in water use in cacao agroforestry system over the soil profile, shown as wetter topsoil and dryer conditions in the depth than in monoculture. A negative effect of the cover crop on soil moisture was not registered. Also we did not find a significant effect of the soil group on cacao performance. But generalizations from the agroforestry systems in this study are rather unsafe due to different planting densities and species used in cacao agroforestry systems worldwide and the variation of soil types where cacao is grown.

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