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Spatial-temporal soil moisture dynamics under different cocoa production systems

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ABSTRACT

Soil moisture has high spatial and temporal variability, depending on topography, soil texture, vegetation and meteorological conditions. It influences many processes in the soil and supplies water to the vegetation. This is often a limiting factor in agricultural production.

Over an 18-month period, we measured soil moisture dynamics down to a depth of 70 cm in a long-term trial in Bolivia comprising six different land-use systems, i.e. cocoa monocultures and agroforestry systems, both under organic and conventional management, successional cocoa agroforestry systems and a natural fallow. Soil was heterogeneous over the area and in depth. We identified and separated two soil groups which differed in both, texture and soil water retention capacity. Considering the two groups, we assessed the effect of the different land-use systems on soil moisture dynamics and plant available water on the one hand, and how different soil moisture conditions affect growth and production of cocoa on the other.

In monocultures with shallow rooting cocoa only, soil moisture decreased mainly in the uppermost soil layer during the dry season and the lower layers kept more moisture year round. In agroforestry systems soil moisture decreased homogeneously over the soil profile, implying a complementarity in water use of cocoa and deeper rooting trees. The uppermost soil layer in the agroforestry systems had higher soil moisture than in the monoculture, demonstrating the role of shade trees to reduce water loss from top soil by evaporation and transpiration of the cocoa. Even though one soil group had continuously higher water availability than the other group, we did not find an effect on the cocoa yield.

Cocoa relies on sufficient water supply, but beside information on the precipitation it is important to know the soil structure and soil water retention capacity when discussing water availability for cocoa production and to consider the heterogeneity of the soil even over small area.

1. Introduction

Soil moisture, together with soil temperature, influences many physical, biological and chemical processes in the soil (Özkan and Gökbulak, 2017) and is a major resource for vegetation growth and agricultural production. It is highly temporally dynamic, especially in tropical regions with distinct dry and rainy seasons. Spatial heterogeneity of soil and pedohydrological properties, i.e. soil moisture retention capacity, can change soil moisture drastically in a given field or area, which makes the determination of soil–vegetation interactions complicated (van Pelt and Wierenga, 2001). Moisture dynamics depend on topography, soil texture, vegetation and meteorological conditions (Mittelbach and Seneviratne, 2012). Plant available water depends on both the soil properties that determine soil suction and the local climate (Denmead and Shaw, 1962). Understanding spatial-temporal patterns and functioning of soil moisture dynamics are of interest when land-use changes lead to the removal of the native vegetation (Özkan and Gökbulak, 2017) or when water availability for crop production is limited (Huth and Poulton, 2007). The complexity of moisture dynamics is enhanced in mixed cropping systems, e.g. agroforestry systems, where rooting systems might compete for the same soil resources (Schroth et al., 1999) or have complementary spatial exploitation over a larger soil profile with deep rooting trees (Ong et al., 1991). Soil moisture dynamics are best described using classical spatial and temporal statistical parametric values that explain the mean temporal dynamics and the variability over the area (Starks et al., 2006; Martínez-

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Fernández and Ceballos, 2005; Mittelbach and Seneviratne, 2012).

Cocoa (*Theobroma cacao* L.) cultivation ranges from full-sun monocultures to highly diverse agroforestry systems (Schroth et al., 2004). Cocoa relies on humid conditions; dry spells with < 100 mm rainfall in three consecutive months can be critical for production. In many cocoa producing areas, annual precipitation is just slightly above the recommended minimum of 1250 mm of rainfall per year (Zuidema et al., 2005) that is distributed mainly over the rainy season. Soils should be well drained to avoid water logging during the rainy season, but water retention capacity must be sufficient to maintain soil moisture during the dry season (Alvim, 1960). It is projected that cocoa producing areas worldwide will be exposed to climatic variations coming along with an increase in temperature and a shift in precipitation patterns, i.e. drier conditions during the dry season (Läderach et al., 2013). This might be intensified by the recurrence of global events like El Niño and La Niña (Seiler et al., 2013). Since irrigation is not available for small scale farmers and root pruning is not practiced, the cocoa production system itself must be adapted to local climatic conditions and protect the crops from extreme events.

Amongst other benefits and trade-offs (e.g. Steffan-Dewenter et al., 2007; Tscharntke et al., 2011; Vaast and Somarriba, 2014), agroforestry systems have the potential to provide physiologically less stressful conditions for the understory cocoa compared to monocultures. By buffering temperature extremes and decreasing maximum vapor pressure deficit (Niether et al., submitted), agroforestry systems may lower the evapotranspirative demand within the cocoa stratum (Beer et al., 1998) and increase the water-use-ratio of the shaded crop (Ong and Swallow, 2003). Furthermore, it has been reported that cocoa agroforestry systems have a higher soil organic matter content (Monroe et al., 2016) and stable aggregates (Gama-Rodrigues et al., 2010), improved infiltration and reduced drainage (Ong and Swallow, 2003) in comparison to other sites used for agricultural production. On the other hand, the high primary production of agroforestry systems compared to monocultures is attributed to a higher water use by an increased transpiration (Ong and Swallow, 2003). Information on belowground interactions between cocoa and shade trees according the moisture dynamics is scarce. Also little is known about the effect of soil cover crops in cocoa production systems on the soil water resources, as they reduce run-off and evaporation from the soil (Schroth et al., 2001) but also consume water by transpiration.

In this study we describe the spatial-temporal soil moisture dynamics on an alluvial terrace in the region Alto Beni, at the foothills of the Bolivian Andes. A long-term trial on cocoa production was established to compare cocoa monocultures, agroforestry systems and successional agroforestry systems with a natural fallow. Monocultures and agroforestry systems were both under conventional and organic management, latter including a leguminous cover crop (Schneider et al., 2016). Soil texture was already observed to differ over the trial area (Gramlich et al., 2016). We studied the moisture retention capacity of the soil and actual soil moisture, and the influence of vegetation cover on the relative extractable water. We hypothesized that (i) the water availability for plants differs over the trial area; (ii) water resources over the profile can be used complementarily by roots of agroforestry trees exploiting depths below the shallow rooting cocoa; (iii) more moisture is available in the topsoil layer in agroforestry systems because of the shade canopy which reduces the water loss by transpiration of the cocoa and by evaporation from soil; and that (iv) the positive and negative effects of the cover crop in the organically managed systems are balanced and as a result do not negatively affect the soil moisture content compared to conventionally managed systems without cover crops. Finally we tested (v) if soil groups that were differentiated according to their moisture retention capacity affect the performance of the cocoa production systems, here measured as tree growth and bean production.

2. Materials and methods

2.1. Study area, soil formation and regional climate

The study site Sara Ana is located in the region Alto Beni at the foothills of the Bolivian Andes. The climate is characterized by a mean annual temperature of 25.2 °C and mean annual relative humidity of 83.0%. The annual precipitation of on average 1440 mm falls mainly (78%) during the rainy season, i.e., from October to April (SENAMHI, 2015; Niether et al., submitted). Land-use of the region is dominated by secondary forest and agricultural production, including cocoa (Andres et al., 2016). Soil formation was developed by irregular flooding and alluvial deposits of the river Alto Beni in the Holocene.

The experimental trial, where this study was conducted, comprises 6 ha that lie on a flat alluvial terrace 380 m.a.s.l. at 15°27′36.60″S and 67°28′20.65″W. Soils are classified as Luvisols and Lixisols (Schneider et al., 2016). These are strongly weathered soils under a tropical climate with distinct rainy and dry seasons. Pedogenesis with clay lessivation down to an argic subsurface horizon results in a clay-enriched subsoil (FAO, 2006) that causes heterogeneous water retention properties on horizontal and vertical scale influencing the water availability for the plants over the area and in the soil profile.

Precipitation in 2014 and 2015 was measured at the local weather station in Sara Ana (SENAMHI, 2015) and data were verified with four rain gauges installed at 1 m height on pasture in proximity to the studied plots.

2.2. Experimental design

The long-term trial in Sara Ana was established at the end of 2008. It consisted of a randomized complete block design with four replications comparing five different cocoa production systems: full-sun monocultures (MONO) and agroforestry systems (AF) both under organic (ORG) and conventional (CONV) farming and a highly diverse cocoa successional agroforestry system (SAFS) under organic farming. Non-cultivated plots (fallow) of the same age following a natural succession (BAR) were included as natural control. The five cocoa production systems and the fallow are hereafter jointly named as land-use systems. The former vegetation (fallow) was slashed and afterwards unfertilized maize was cropped with canavalia for one season and soil analyses were performed to assess soil homogeneity of the terrain and to allocate the blocks (Schneider et al., 2016). Data were collected in three replications.

Each plot had a size of 48 by 48 m, and data collection took place in the inner 24 by 24 m net plot. Cocoa trees were spaced 4 by 4 m, and both AF and SAFS were diversified with woody shade trees and plantain or banana (Schneider et al., 2016). Land-use systems differed by their stem density and the resulting leaf area index and soil temperature (Table 1). BAR plots without cropping, management and a distinct stock density were dominated by fast growing pioneer succession species like *Cecropia* spp.

Locally prepared compost was applied to cocoa trees once a year in organically managed production systems and mineral fertilizer twice a year in conventionally managed ones. For both fertilization types, 50% of the dose applied in the MONO was applied in the AF. Cocoa trees in SAFS were not fertilized. A leguminous perennial soybean (*Neonotonia wightii* (Wight & Arn.) J.A. Lackey) was planted as soil cover crop in MONO ORG and AF ORG, the space around the cocoa stems was kept free from vegetation (Schneider et al., 2016).

2.3. Determination of pedohydrological characteristics and clustering of soil groups

Four soil sampling sites in each net plot were allocated along a V-shaped transect of 52 m crossing cocoa and shade tree rows (Nicklas, 2006) summing up to 72 sampling sites evenly distributed over the

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