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Research paper

Does shade tree diversity increase soil fertility in cocoa plantations?

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ABSTRACT

Complex agroforests have been promoted as a potential solutions to address trade-offs between environmental conservation efforts and the need for increased agricultural productivity for smallholder farmers in the tropics. However, the effects of tree diversification on soil fertility in tropical agroforests remain unclear. In this study, we examine whether tree diversification in cocoa plantations is associated with soil fertility benefits and can contribute to soil restoration after deforestation. We tested for positive associations between increasing tree species diversity and increased soil aggregation, soil nutrients and microbial communities across a diversity gradient ranging from cocoa monocultures to complex cocoa agroforests. Secondary forests and primary forests were used as reference ecosystems. Increase in tree diversity within cocoa plantations did not increase soil fertility parameters in topsoil layers or cocoa yields. Mean soil C contents were 8% lower, mean weight diameter of aggregates 48% lower and total bacterial biomass 35% lower in cocoa plantations than in primary and secondary forest systems, whereas soil P content was 22% higher. Across all land-use systems, microbial biomass was greater in sites with higher soil carbon contents and soil aggregation. This suggests soil function restoration in terms of microbial communities, soil C and aggregate stabilization in secondary forests. However, in cocoa plantations tree diversification alone may not be an effective solution to mitigate soil degradation after deforestation. Rather, preserving remaining forests or promoting farming approaches that allow for secondary forest regeneration (e.g. implementing forest strips and regular fallow rotations) might have a more substantial impact on soil health.

1. Introduction

Agroforests have been promoted as potential solutions to bridge biodiversity conservation efforts and the need for increased agricultural productivity in tropical countries (Tscharntke et al., 2012). Benefits of intercropped shade trees are proposed to range from microclimate regulation (Beer et al., 1998) to alternative income sources for farmers (Tscharntke et al., 2011) or improved nutrient cycling efficiency (Schroth, 1998). Increasing tree species diversity is thought to maintain soil fertility through several mechanisms. For example, differences in input quantity and quality, rooting architecture and other functional traits among tree species can lead to altered litter decomposition rates and changes in substrate quality, which can indirectly impact soil microbiota (Scherer-Lorenzen et al., 2007). Increasing tree species diversity at the ecosystem level can also improve resource use complementarity, minimizing nutrient losses through leaching and erosion and potentially improving nutrient recycling and nutrient availability for crops at the ecosystem level (Ahenkorah et al., 1987; Mäder et al., 2002; van Ruijven and Berendse, 2005). Although studies conducted in Togo (Dossa et al., 2008) and Ghana (Ofori-Frimpong et al., 2007) have found improved soil fertility in complex coffee or cocoa agroforests compared to monocultures, data remains lacking about cumulative effects of increasing richness and abundance of tree species ("tree diversification") on soil fertility in tropical agroforestry systems.

While soil fertility is determined by many key physical, chemical and biological properties (Doran and Parkin, 1994), microbial communities' role in the regulation of important nutrient cycling processes such as decomposition or aggregate formation is well recognized (e.g. Swift et al., 1979; Six et al., 2004). Many studies have documented soil microbial communities' responses to changes in vegetation composition (e.g. Wardle et al., 2004), and we similarly expect increases in tree diversity to impact soil microbial activity in cocoa agroforests. Soil microbial communities are also highly sensitive to environmental changes and are thus useful indicators for changes in soil conditions

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caused by land-use change (Six et al., 2006). However, few studies have documented the effects of increasing tree diversity on microbial communities in tropical agroforestry systems.

As a result, the overall benefits of increased tree diversity on soil fertility in cocoa agroforests remain ambiguous. On one hand, increased plant species diversity has been directly linked to spatial and temporal resource partitioning and improved functional complementarity (Hooper and Vitousek, 1997; van Ruijven and Berendse, 2005). For example, certain tree roots can function as safety nets, minimizing leaching via stratification and recycling nutrients from deeper soil horizons to soil surface layers (Van Noordwijk and Purnomosidhi, 1995). However, intercropped trees in agroforests might also compete with crops for nutrients (Sanchez, 1995) or light resources (Clough et al., 2011). A majority of the data suggesting a positive effect of plant species diversity on soil processes has been derived from experimental studies conducted in controlled plantation trials and/or in temperate grassland ecosystems (Tilman et al., 1996; Scherer-Lorenzen et al., 2007). While such studies are invaluable in determining causal relationships between plant diversity and below-ground processes, they may not easily translate to other natural environments and cropping systems. In contrast, insights derived from observational studies conducted in real-world farming systems are scarce, yet could provide complementary information that helps us understand the functioning of agroecosystems processes under field conditions (Vilà et al., 2005).

Indonesia is currently the third largest global cocoa exporter, and more than 60% of the country's cocoa is grown on the island of Sulawesi, which faces increasing rates of deforestation and agricultural expansion (McMahon et al., 2015). The region thus constitutes a relevant case study for the potential effects of cocoa agroforest diversification on soil fertility. After an initial period of high productivity, cocoa farmers in Sulawesi are now faced with rapidly declining cocoa yields linked to unsustainable management practices, increased pest and disease incidence and increased soil degradation (McMahon et al., 2015). This decline in productivity has led farmers to abandon existing plantations and seek out new land, leading to further deforestation and threatening remaining rainforest areas. Improving the sustainability of established cocoa plantations in the region should thus be a priority.

Our principal objective is to determine whether tree diversification in cocoa plantations can provide soil fertility benefits and contribute to soil restoration after deforestation, ultimately contributing to the increased sustainability of cocoa cultivation systems in Southeast Sulawesi. To quantify the effects of tree diversification on soil fertility in cocoa plantations we compared soil fertility indicators (total carbon (C), nitrogen (N), phosphorus (P), available P, pH, cation exchange capacity (CEC), base saturation, soil aggregation, bulk density and phospholipid fatty acid (PLFA) composition) along a gradient of increasing tree species diversity. To assess the extent to which cocoa agroforests might contribute to soil restoration following deforestation, we further examine how the effects of tree diversification on soil fertility in cocoa plantations compare to soil fertility levels in secondary and primary forests.

2. Material & methods

2.1. Description of the study

We conducted our study in the Konawe province in Southeast Sulawesi, Indonesia (3.58°S, 122.30°E), where *Theobroma cacao* (cocoa) is the most prevalent cash crop. While traditionally cocoa plantations are often established by thinning primary forests (Tscharntke et al., 2011), in Sulawesi cocoa seedlings are planted on land completely cleared from forests by manual cutting of trees and undergrowth. Following plot establishment, *Gliricidia sepium* (gliricidia) trees are commonly intercropped with cocoa seedlings, mainly to provide shade protection. In older plots, farmers reduce the number of gliricidia trees, but fruit and timber trees are sometimes planted to supplement incomes. Thus, much of the cocoa in the region is grown in agroforests with varying levels of tree diversity.

Table 1
Soil texture range across three communities in Southeast Sulawesi that were selected as study locations for our study. Means and standard errors are shown for percentage sand, silt and clay contents.

Site	Plots	Sand (%)	Silt (%)	Clay (%)
1. Wonuahoa	18	27.8 ± 8.7	37.1 ± 5.9	36.0 ± 5.3
2. Asinua Jaya	15	37.0 ± 6.7	30.2 ± 9.9	32.9 ± 4.2
3. Lawonua	15	18.2 ± 7.2	46.9 ± 18.5	34.9 ± 13.5

Study sites were selected in the communities of Lawonua, Wonuahoa and Asinua Jaya. Soils in the region are dominated by weathered *orthic acrisols* in the mountains and *dystric fluvisols* in the floodplain (FAO-UNESCO, 1979), and the selection of three separate villages allowed us to test our hypotheses across different soil types in the study area (Table 1). Annual precipitation is 2080 mm (1982–2012 average) and is highly seasonal, with most rain falling during the wet season from January to June. Mean daily temperatures range between 25 °C and 28 °C, depending on time of the year and elevation (Climate-Data.org, 2016).

2.2. Plot selection and characterization

We selected twelve cocoa plots measuring 30 m × 30 m in each village (for a total number of 36 cocoa plots) to represent the variation in shade tree cover and tree species diversity observed in the study region ("diversity gradient", Fig. 1a). To obtain an adequate diversity gradient ranging from low to high tree species diversity, selected plots were evenly distributed across the following typologies, which we defined based on the number of intercropped tree species per plot: cocoa monocultures, simple agroforests, intermediate agroforests and complex agroforests (Table 2). In simple agroforests, the most common species intercropped with cocoa was gliricidia, followed by banana (*Musa paradisica)*. In intermediate agroforests, cocoa was typically intercropped with 3–4 fruit or timber tree species. In complex cocoa agroforests, cocoa was intercropped with about 5–9 tree species. Most cocoa plots were established within 3–5 years of each other, and on average cocoa trees in our study plots were 13 years old (Table 2).

To compare soil properties between cocoa plantations and forested areas, we selected three secondary forest plots in each community and three additional primary forest plots in Wonuahoa, leading to a total of 48 plots. Secondary forest systems were established at least 10 years after abandonment of old cocoa fields. They were dominated by a mix of domesticated crop trees (*Theobroma cacao*, *Gliricidia sepium*, *Gmelina arborea*) and local forest trees (*Mischocarpus sundaicus*, *Albizia procera*, etc.). Selection criteria for primary forest plots included plots that had more difficult access for farmers and appeared to be undisturbed both in terms of soil and vegetation. Tree species composition in these primary forests plots was dominated by local species (*Castanopsis buruana*, *Aporosa purpurescens*, etc.). All cocoa and secondary forest plots were identified and sampled between March and June 2014 and all primary forest plots in May 2015. Four plots across the diversity gradient in cocoa plantations and one secondary forest plot were re-sampled in 2015 to verify that 2014 and 2015 data sets are comparable. We compared total soil C, N and P content and found no significant differences between the two years. To minimize the risk of bias across all selected cocoa and forest sites we only included plots with homogenous vegetation cover and soils. Wherever possible we excluded plots located on sloped terrain or those that contained visible man-made structures or disturbances (e.g. hills or trenches).

In each plot we recorded total number of tree species (s) and proportion (p) of individuals per species to quantify tree diversity using the Shannon Diversity index (Shannon and Weaver, 1964):