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Shade trees have limited benefits for soil fertility in cocoa agroforests

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ABSTRACT

Agroforestry is often promoted as a sustainable agricultural practice that can ameliorate causes of declining yields, such as soil degradation. However, despite the often-stated potential of agroforestry, quantitative data on the benefits of shade trees are limited to relatively few cropping systems, particularly maize and coffee. Furthermore, agroforests are not cost-free and the benefits of agroforests might not be sufficient to outweigh these costs in all cropping systems or environments. Here we quantify costs and benefits of agroforests for cocoa production in Ghana, West Africa. Specifically, we quantified the ability of shade trees to increase soil carbon stocks and soil fertility (i.e. total soil carbon, nitrogen and phosphorus, available phosphorus and potassium, cation exchange capacity, soil aggregation, pH, and foliar nitrogen and phosphorus concentrations), and investigate if these benefits are sufficient to outweigh the negative effects of shade trees on cocoa growth and yields. We measured cocoa yields, soil fertility and carbon-sequestration under individual shade trees, and in 30 × 30 m plots that were distributed along a gradient of shade-tree cover (plot-scale). We found localized positive effects of individual shade trees on soil carbon and nitrogen content, as well as soil aggregation. However, we found no evidence for positive effects of agroforests via improved soil fertility or carbon-sequestration with increasing shade-tree cover at the plot scale, a scale that more closely matches the scale at which agroforests are managed. Cocoa growth was lower under individual shade trees and decreased with increasing shade-tree cover in plots, and cocoa yields also decreased with increasing shade-tree cover. Our results indicate that the benefits of agroforestry for soil fertility and carbon sequestration in cocoa cultivation systems might not be as extensive as believed, and may not be sufficient to compensate for short-term costs to production.

1. Introduction

Agroforestry – the deliberate inclusion of trees in agricultural systems – is often believed to mitigate ongoing threats to agricultural production, while also maintaining essential ecosystem services (Jose, 2009; Tscharntke et al., 2011). The benefits associated with agroforestry, including climate buffering, carbon sequestration, pathogen regulation, and improvements in soil fertility, are often taken to be broadly applicable to a wide range of cropping systems and climatic zones, but the majority of the quantitative evidence is concentrated in just a few, particularly coffee and maize (Sanchez, 1995; Rhoades, 1996; Kwesiga et al., 2003; Jose, 2009; Nair and Nair, 2014). The extent to which the benefits of agroforestry are transferrable to other systems is largely unknown but important given that agroforests are widely promoted (Tscharntke et al., 2011; Vaast et al., 2016).

One of the more significant crops for which production in agroforests is promoted is cocoa. Worldwide demand for cocoa continues to increase even as production declines as a consequence of multiple factors including pests and disease, declines in soil fertility, and an increasingly hotter and drier climate (Franzen and Borgerhoff Mulder, 2007; Clough et al., 2009; Läderach et al., 2013; Vaast and Somarriba, 2014). Given these ongoing threats, implementing cocoa production in agroforests would seem to make intuitive sense but data that is specific to cocoa systems is limited. Furthermore, agroforests are not cost-free and the benefits of agroforests might not be sufficient to outweigh these costs in all cropping systems or environments. Most critically, agroforests often result in reductions in short-term yields (Sanchez, 1995; Tscharntke et al., 2011), which is a major reason it is difficult to encourage their implementation. This is particularly the case among small-holder cocoa farmers in Africa (Ruf, 2011). If agroforests are to best meet future sustainability needs it is necessary to demonstrate that the benefits are sufficiently large to justify their implementation.

One of the major proposed benefits of agroforests is their ability to mitigate the worst effects of soil degradation by maintaining soil

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fertility. Such a benefit would be particularly important for cocoa systems, which tend to be nutrient-depleted because nutrients exported from the system with each crop are generally not replaced through fertilization (Appiah et al., 1997; Hartemink, 2005). While there is some anecdotal evidence from interviews with farmers that shade trees improve soil fertility in cocoa systems (e.g. Anglaaere et al., 2011; Atkins and Eastin, 2012; Dumont et al., 2014), the existing empirical evidence is limited and equivocal. With respect to soil carbon (C), Ofori-Frimpong et al. (2007) showed increases, while Gockowski and Sonwa (2011), Jacobi et al. (2014), and Mohammed et al. (2016) showed no effect of shade trees. With respect to mineral nutrients essential for plant growth, Ofori-Frimpong et al. (2007) showed increases in nitrogen (N), phosphorus (P) and potassium (K) in a fertilized, research station trial; Isaac et al. (2007) showed increases in one soil exchangeable nutrient (K) but not in others (N and P), but generally increased foliar nutrient levels of cocoa under individual shade trees. Given these limited and contrasting results, it remains an open question whether shade trees generally increase soil fertility and perhaps more importantly, whether these increases are sufficient to sustain yields. Moreover, to our knowledge no study has quantified the effects – positive or negative – of shade trees on an array of soil fertility parameters in cocoa agroforestry systems as implemented by farmers themselves; that is, in existing low-input, small-holder fields and along a continuum of shade-tree density.

An additional benefit of agroforests rests on their potential to sequester carbon. Agroforests have long been considered a greenhouse gas mitigation strategy, including under the Kyoto Protocol, and the climate mitigation potential of agroforests remains a major motivation for promoting their implementation (Nair et al., 2009). While it is clear that agroforests can store substantial C in above-ground biomass (Gockowski and Sonwa, 2011; Jacobi et al., 2014; Obeng and Aguilar, 2015), substantial questions remain about the ability of agroforests to enhance C-sequestration in soils. In particular, while soil C tends to be higher in cocoa systems compared to annual production systems (Guo and Gifford, 2002; Dechert et al., 2004), it is unclear if the addition of shade trees in cocoa systems provides any additional C-sequestration benefit (see contrasting results in Ofori-Frimpong et al. (2007), Gockowski and Sonwa (2011), Jacobi et al. (2014), and Mohammed et al. (2016)). Furthermore, it is also important to understand the extent to which C-sequestration in cocoa agroforests compares with the C-sequestration ability of the natural forests that they have replaced (Guo and Gifford, 2002; Leuschner et al., 2013; Obeng and Aguilar, 2015).

To further our understanding of the extent to which agroforests might improve the sustainability of cocoa production, we addressed the following question: do shade trees in cocoa agroforests increase soil carbon stocks and soil fertility, and are these benefits sufficient to result in net positive effects of shade trees on cocoa growth and yield? Importantly, we investigated these questions using two commonly used sampling approaches. First, we determined the effect of individual shade trees on soil fertility. To quantify the effects of individual shade trees we chose shade trees that were growing with cocoa but isolated from the canopy of other shade trees. (Fig. 1a). Second, we extended our assessment to determine if the effects of individual shade trees can be used to understand effects of larger numbers of trees across plots of larger size (plot-scale, Fig. 1b). Both sampling approaches (individual-tree and plot-scale assessments) are commonly used to study tree-understory-interactions, but the outcome of tree-understory interactions can manifest differently depending on the approach used (Riginos et al., 2009). Comparing these different approaches for assessing the effectiveness of shade trees on cocoa production is important because we need to know if assessments of the effects of individual shade trees can provide adequate information for farm management at larger scales.

2. Materials and methods

2.1. Study site

The study was done in one of the major cocoa growing regions in Africa, in the moist semi-deciduous tropical zone of the Ashanti Region of Ghana, around the villages Gogoikrom, Katatwoa and Akonkyi, located in the Atwima district (06°40′ N and 01°57′ W). The soils in the area are dominated by Acrisols. Mean annual precipitation ranges between 1700 and 1850 mm with rains occurring in two separate rainy seasons (March to July and September to November). Mean monthly temperatures range between $27-31^{\circ}$ and mean relative humidity is generally high throughout the year (75–87%, Anglaaere et al., 2011). The study area contains a large number of cocoa farms with variable shade-tree cover (including monocultures), as well as a selectively-logged natural forest remnant.

2.2. Assessing the effects of individual shade trees

2.2.1. Selection of individual shade trees

To assess the local effects of individual shade trees on soil fertility parameters and cocoa growth, we selected 32 individual shade trees across eleven cocoa farms in May 2014 (Fig. 1a, Table A.1 in Appendix A). All of the selected shade trees in this sampling approach were surrounded by cocoa and had cocoa growing in their subcanopy, however, each individual shade tree was isolated from the canopy of other shade trees by at least 30 m. This approach allowed us to quantify the local effects of individual shade trees within cocoa farms. Each selected shade tree represented a different shade-tree species commonly found in cocoa farms in the Atwima district (cf. Anglaaere et al., 2011; personal observation). Our selection included most species recommended for use in Ghanaian cocoa farms (Opoku-Ameyaw et al., 2010). Species were not replicated because we were interested in general effects of shade trees across the full range of species commonly found in Ghanaian cocoa farms. In the rest of the manuscript we will refer to these trees as “individual shade trees”.

For each individual shade tree we assessed effects on soil fertility and cocoa growth parameters by taking measurements directly under the shade-tree canopy (‘subcanopy’) and in open control areas where cocoa grows in the absence of shade trees (‘open’; Fig. 1a). Subcanopy areas and open areas for each shade tree were sampled as pairs within the same farm, so that each shade tree had its own paired control location. Open areas were sampled within cocoa but away from the influence of the focal shade tree, at a minimum distance of twice the radius of the canopy from the trunk of the shade tree, or at a minimum distance of 12 m from the canopy edge if the canopy radius was less than 5 m. Sampling procedures for each parameter are described in the sections below (section 2.2.2 and 2.2.3).

2.2.2. Soil sampling and analysis

In May 2014, we collected two soil samples in the subcanopy area, and two soil samples in the open areas away from shade trees, around each individual shade tree. Sampling was done under the canopy of cocoa trees, in both subcanopy and open areas (Fig. 1a). All subcanopy soil samples were collected, at a distance of half the radius of the canopy from the base of the trunk of each shade-tree. The purpose of this sampling approach was to ensure samples were always taken in the subcanopy area of shade trees and resulted in an average sampling distance from the trunk of each shade tree of 2.93 ± 0.2 m.

Soils were sampled at three depths after carefully removing the litter layer; topsoil samples (0–15 cm) were sampled with a hammer corer (Ø 5.5 cm), and subsoil samples (15–30 cm and 30–50 cm) were collected using a soil auger. Soil bulk density was calculated based on the weight of topsoil core samples after correcting for soil moisture and the mass and volume of roots and stones (Culley, 1993). Topsoils were then gently sieved through an 8 mm sieve and air-dried. After drying,