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# Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems

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ABSTRACT

Agroforestry systems provide diverse ecosystem services that contribute to farmer livelihoods and the conservation of natural resources. Despite these known benefits, there is still limited understanding on how shade trees affect the provision of multiple ecosystem services at the same time and the potential trade-offs or synergies among them. To fill this knowledge gap, we quantified four major ecosystem services (regulation of pests and diseases; provisioning of agroforestry products; maintenance of soil fertility; and carbon sequestration) in 69 coffee agroecosystems belonging to smallholder farmers under a range of altitudes (as representative of environmental conditions) and management conditions, in the region of Turrialba, Costa Rica. We first analyzed the individual effects of altitude, types of shade and management intensity and their interactions on the provision of ecosystem services. In order to identify potential trade-offs and synergies, we then analyzed bivariate relationships between different ecosystem services, and between individual ecosystem services and plant biodiversity. We also explored which types of shade provided better levels of ecosystem services. The effectiveness of different types of shade in providing ecosystem services depended on their interactions with altitude and coffee management, with different ecosystem services responding differently to these factors. No trade-offs were found among the different ecosystem services studied or between ecosystem services and biodiversity, suggesting that it is possible to increase the provision of multiple ecosystem services at the same time. Overall, both low and highly diversified coffee agroforestry systems had better ability to provide ecosystem services than coffee monocultures in full sun. Based on our findings, we suggest that coffee agroforestry systems should be designed with diversified, productive shade canopies and managed with a medium intensity of cropping practices, with the aim of ensuring the continued provision of multiple ecosystem services.


## 1. Introduction

Agroforestry systems in tropical landscapes provide a series of ecosystem services that help sustain crop production, improve farmersí livelihoods and conserve biodiversity (Jose, 2009; Tscharntke et al., 2011). Shade trees and other companion plants in agroforestry systems can produce fruits (Rice, 2011; Cerda et al., 2014), timber, firewood and other products for sale or household use (Somarriba et al., 2014), thereby diversifying the sources of income for farmers and contributing to food security. The roots and leaf litter of shade trees, especially leguminous trees, improve nutrient recycling and soil quality (Beer et al., 1998) and can help reduce soil erosion (Gómez-Delgado et al., 2011). Shade trees are

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also useful for protecting crops from strong winds, high temperatures and extended dry periods (Schroth et al., 2009; Jha et al., 2014). Shade trees and other woody perennials contribute to the conservation of animal and plant biodiversity, and sequester carbon from the atmosphere, thereby contributing to climate mitigation (Jha et al., 2011; Somarriba et al., 2013; Deheuvels et al., 2014).

Yet agroforestry systems can also result in disservices and antagonistic effects (Zhang et al., 2007; Power, 2010). A known drawback of agroforestry systems is that the yields of the main crop are often lower than those in full sun systems (López-Bravo et al., 2012), at least in the short term. With increasing shade cover, the relative yield of the main crop tends to decrease (Zuidema et al., 2005) due to greater competition for light, water and nutrients in soil between trees and the main crop. Another potential drawback of agroforestry systems is the higher labor requirements to manage trees and other plants. Agroforestry systems can favor or disfavor the attack of pathogens and insects depending on the composition, structure and management of the shade canopies (Staver et al., 2001; Avelino et al., 2006; Cheatham et al., 2009; Pumariño et al., 2015).

Despite the recognition that agroforestry systems can potentially provide diverse ecosystem services, there is still limited understanding on how shade trees affect the provision of multiple ecosystem services and about the potential trade-offs or synergies among them. Most studies in agroforestry systems have focused on a single ecosystem service (Jose, 2009), and have not examined relationships among various ecosystem services. In addition, most studies have only considered the individual effect of shade on ecosystem services, underestimating other factors, such as management practices and environmental conditions, which may interact with shade to provide ecosystem services (Staver et al., 2001; Avelino et al., 2006). However, a good understanding of different factors, including their interactions, affecting the provision of ecosystem services, and the analysis of relationships (trade-offs or synergies) among ecosystem services, are needed to design high performing agroforestry systems (Rapidel et al., 2015).

Understanding the provision of ecosystem services by agroforestry systems is particularly important for the coffee sector in Central America which is currently under severe stress. A chain of events, including decreasing coffee prices, increasing production costs, and an outbreak of coffee leaf rust (*Hemileia vastarix* Berkeley and Broome) since 2012, has significantly reduced coffee production. Following the coffee rust outbreak, farmers were forced to stump their impacted coffee plantations to rejuvenate coffee trees or to renew them with new coffee varieties, or even to replace them with new crops (Baker, 2014; Avelino et al., 2015; McCook and Vandermeer, 2015). For instance, 50% of coffee areas have disappeared in the Volcan Central Talamanca Biological Corridor in Costa Rica between 2000 and 2009 (Bosselmann, 2012), and 35% of the coffee areas in southern Guatemala between 2000 and 2004 (Haggar et al., 2013). The conversion of coffee plantations to other land uses results in the loss of shade trees and other vegetation and negatively affects plant biodiversity (Zhang et al., 2007; De Beenhouwer et al., 2013). Information on the potential benefits provided by shade trees associated with coffee plantations could encourage decision makers, technicians, and farmers to maintain and/or increase land uses under coffee agroforestry systems, and stem the ongoing loss of these systems (Cheatham et al., 2009; Jose, 2009).

The objectives of this study were i) to assess the effectiveness of different types of shade of coffee agroecosystems in providing multiple ecosystem services under different environmental and management gradients, and ii) to understand the relationships (trade-offs or synergies) across different ecosystem services and plant biodiversity. We quantified indicators of four major ecosystem services: 1) regulation of pests and diseases; 2) provisioning of agroforestry products (coffee, bananas, other fruits, timber); 3) maintenance of soil fertility; and 4) carbon sequestration, in coffee agroecosystems belonging to smallholder farmers under a range of altitudes (as representative of environmental conditions), management practices and types of shade. We hypothesized that the effectiveness of different types of shade in providing ecosystem services depends on their interaction with coffee management and altitude where coffee is grown, and that trade-offs or synergies could occur among certain ecosystem services. Based on our findings, we highlighted key aspects that should be considered for the design and management of coffee agroecosystems to ensure the continued provision of multiple ecosystem services.

## 2. Materials and methods

### 2.1. Coffee plot network and experimental design

A coffee plot network (69 plots) was established in the canton of Turrialba, Costa Rica. Turrialba is located in a premontane wet forest life zone, with an mean annual rainfall of 2781 mm and a mean annual temperature of 22.2 °C (averages of the last 10 years), with small variations among months. In this area, coffee is grown from 600 to 1400 m.a.s.l. (meters above sea level). Farms in higher elevations experience slightly wetter and cooler temperatures compared to farms at lower elevations.

The plot sampling strategy had the objective to select coffee plots of different types of shade across altitudinal and management intensity gradients. Plots were selected with contrasting characteristics in the botanical composition and structure of shade canopies (in terms of species richness, abundances and trunk basal areas), with contrasting coffee cropping practices (in terms of different types of practices and frequency of applications), and at different altitudes. However, in order to limit variations and avoid confounding effects of different factors (Clermont-Dauphin et al., 2004), we chose coffee plots that shared three main characteristics: i) they were owned by smallholder farmers, ii) had coffee plants (*Coffea arabica* L.) of the dwarf variety *Caturra* as the unique or dominant variety, which is the most common variety in Costa Rica and in other countries of Central and South America (McCook and Vandermeer, 2015), and iii) were located on soils belonging to the order Inceptisols, suborder Udepts. These soils in Turrialba are considered to have moderate fertility but with problems of acidity (CIA, 2016).

In each coffee plot of the network, an experimental subplot composed of eight coffee rows with 15 plants each was demarcated in a representative place of the plot. Eight coffee plants (and three branches per plant) were marked, one plant per row, inside the experimental subplot. These eight plants were used for measurements of pests and diseases and coffee yields, and for sampling soil subsamples near them. For the measurement of characteristics of the shade canopy, a circular area of 1000 $m^2$ was established in the center of the experimental subplot (17.8 m radius).

### 2.2. Measurements and calculations of the factors studied

#### 2.2.1. Altitude

The altitude of each coffee plot was measured with a GPS. The mean altitude ± standard deviation of all coffee plots was 877 ± 126 m.a.s.l., ranging from 646 to 1107 m.a.s.l.

#### 2.2.2. Management intensity index

Data on the management were obtained through semi structured interviews with farmers. A management intensity index was calculated for each coffee plot. The calculations were based on existing indices of management intensity used in coffee studies (Mas and Dietch, 2003; Philpott et al., 2006). In the present study, the calculations included 11 cropping practices commonly applied in