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Delicate balance between pest and disease injuries, yield performance, and other ecosystem services in the complex coffee-based systems of Costa Rica

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ABSTRACT

Pests and diseases are the main yield-reducing factors in simplified agricultural systems. Their role in complex, diverse, agricultural systems may, however, be less apparent because of the many interactions in which they are involved. However, it is essential to understand the relationships between pests and diseases, on the one hand, and ecosystem services (including crop production), on the other, to develop sustainable agroecosystems.

Our study aims to illustrate these complex relationships based on the example of coffee agroecosystems in Costa Rica. We analysed a dataset consisting of 107 coffee plots characterized for their topoclimates, soils, coffee plant production characteristics, cropping practices, and pest and disease injuries. Meta-variables were created through cluster analyses to account for these different broad attributes of coffee-based agroecosystems. In particular, coffee injury profiles were determined on the basis of injury levels incurred by pathogens, nematodes, and insects over the course of one growing season. We used correspondence analysis to assess the levels of linkage between injury profiles and other agroecosystem meta-variables. Indicators of biodiversity based on shade diversity and of attainable yield were incorporated in the analysis as additional variables. Four groups of coffee-based agrosystems were identified, ranging from extensive (low-input, perennial polyculture) to intensive (unshaded high-input monoculture). Each group of coffee-based agroecosystem corresponds to varying levels of pest and disease injuries, crop yield, and ecosystem service provision, excluding coffee production. In each group of coffee-based agrosystem, we discussed the drivers of coffee production and explored potential avenues to improve sustainability based on ecosystem services provision. We highlighted that the physical characteristics of the environment, topoclimate and soil characteristics, are the main drivers of injury profiles and of resulting yield losses. Cropping practices and pest and disease management first need to be adapted to these physical characteristics. Where topoclimate and soils favour pest and disease development, potentially leading to heavy yield losses, system diversification can enhance ecosystem service provision, including production of other crops, thus helping to offset low coffee production. Where physical environmental characteristics hamper pests and diseases, increasing ecosystem service provision by incorporating shade trees may be considered, provided that coffee production is not significantly reduced. We conclude that there is an acute need to quantify losses caused by pests and diseases in agroforestry systems, in order to provide a rational basis for growers' decisions and to better determine the value of economic incentives needed for ecosystem service provision.

1. Introduction

Pests, diseases, and weeds negatively impact crop yield (Savary et al., 2006b; Cheatham et al., 2009). However, crop loss estimates are scarce, and vary with the estimation method.

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Widely reported estimates by Oerke, (2006) based on pesticide trials indicate global yield losses to pests, diseases and weeds in the 26–40% range in 2001–2003 for soybean, wheat, cotton, maize, rice, and potatoes, thus confirming earlier estimates by Cramer (1967). Crop loss estimates based on pesticide trials may, however, be biased by over-estimating the impact of some pests and diseases, while under-estimating the effect of others, partly because pesticides often have side effects on crop growth (Savary et al., 1998).

System approaches involving field quantification surveys and simulations through modelling presumably generate crop loss estimates that better account for individual crop pests and diseases and for the losses they collectively cause (Savary et al., 2006a,b). Irrespective of the assessment methodology, however, 20–40% appears to be a conservative estimate of losses due to pests and diseases (Savary et al., 2006b). Chemical controls for pests and diseases have, both, negative externalities on the provision of some ecosystem services, including pollination and pest control, by reducing beneficial organism populations, and on water quality (Cheatham et al., 2009; Power, 2010; Tilman et al., 2002).

It is recognized that biodiversity (species number, species functions) determines the functioning and properties of ecosystems (Tilman et al., 1996; Loreau et al., 2001) particularly their ability to generate goods and ecosystem services (Hooper et al., 2005). Consequently, diversifying agro-ecosystems, e.g. by intercropping plants, has been advocated in order to improve agricultural resiliency and sustainability (Altieri, 1999; Malézieux et al., 2009; Tscharntke et al., 2011; Ratnadass et al., 2012). According to Altieri (1999), biodiversity sustains key ecological services which, if correctly assembled in time and space, can enhance the ability of agroecosystems to internally maintain soil fertility, crop protection, and even productivity. However, this does not imply that diversified agroecosystems are necessarily more productive (Malézieux, 2012), suggesting the existence of trade-offs between production and other ecosystem services. For instance, the productivity of cacao and coffee in complex, rich, and dense agroforestry systems can be very low due to physical constraints (low light availability) and biotic pressures (particularly diseases) (Perfecto et al., 2005; Deheuvels et al., 2012).

Situations have been reported where high biodiversity is actually associated with higher pest and disease injuries (Finke and Denno, 2002), particularly in agroforestry systems (Schroth et al., 2000; Avelino et al., 2011; López-Bravo et al., 2012; Ratnadass et al., 2012). For instance, shade trees may generate conditions that are conducive to some pests and diseases by modifying the microclimate of the understorey vegetation, and some shade trees may also act as alternate hosts (Schroth et al., 2000; Avelino et al., 2011; López-Bravo et al., 2012; Ratnadass et al., 2012). Nevertheless, biodiversity has also often been associated with improved disease and pest control, through mainly: (1) regulation mechanisms involving bio-control agents at the plot and landscape levels (Altieri, 1999; Schroth et al., 2000; Avelino et al., 2011; Ratnadass et al., 2012; Martin et al., 2013), (2) reduced dispersal of pests and pathogens (Ratnadass et al., 2012; Avelino et al., 2012), and microclimate modifications that hamper pest and pathogen development (Schroth et al., 2000; Avelino et al., 2011; Ratnadass et al., 2012).

Despite knowledge on the direct impact of pests and diseases on crop performance, and on the importance of biological diversity in ecosystem service provisioning, the multiple links between planned biodiversity, crop production, and crop pests and diseases have yet to be fully identified and analysed. A multidisciplinary approach to address these multiple links is necessary to first develop hypotheses about the interrelationships between factors within the production system, and in a second time to be able to provide economically viable and environmentally sound recommendations to farmers (Cheatham et al., 2009).

This article specifically addresses this approach under various production settings, for coffee-based agroecosystems in Costa Rica. Coffee-based agroecosystems are particularly relevant for addressing this question because they represent a wide range of vegetational and structural complexities—they range from full sun exposed stands to very complex agroforestry systems, providing habitats for biodiversity and multiple goods and essential ecosystem services (Toledo and Moguel, 2012). In addition, Costa Rica, has developed a program of payments for ecosystem service provision which promotes biodiversity conservation (Le Coq et al., 2011). The program consequently encourages farmers to replant trees on coffee plantations thus enhancing shade cover. Similarly, coffee farmers have to incorporate specific species and use minimum tree densities to obtain certifications that promote biodiversity conservation like bird friendly or Rainforest Alliance. However, these incentives are drawn up without any quantification of the extent to which farmers are actually penalized in terms of reduced yield under agroforestry systems, including coffee yield losses due to pests and diseases (Avelino et al., 2011).

Our research aimed to: (i) improve our understanding of multiple trade-offs between services provided by coffee-based agroforestry systems, pests and diseases, and crop production, and (ii) propose hypothesis by which coffee crop management could be improved to increase growers' income through simultaneous generation of ecosystem services and acceptable coffee yields. We used data from an existing database in which a total of 107 coffee plots had been characterized for their management, including pest and disease control and shade types (as a main source of habitat for biodiversity), their environment, their attainable yield, and pest and disease profiles (Avelino et al., 2007, 2009, 2012). The results are discussed to highlight drivers of pests and diseases and crop production, and develop a framework to improve the sustainability of coffee-based cropping systems.

2. Material and methods

We used a methodological framework developed by Savary et al. (1997) to analyse the relationships between pests and diseases, biodiversity, and crop production. Data were categorized according to: (i) physical characteristics of the environment, (ii) coffee plant production characteristics and crop management patterns, (iii) pest and disease injury profiles, and (iv) attainable yield classes. A biodiversity indicator based on the type of shading involved in the coffee groves was developed and incorporated into our study. Associations between environment, coffee plant and crop management, pests and diseases, and attainable yield groups were assessed by factorial analyses and Chi-square tests. Most of the methods used in this study for plot sampling and description as well as for quantification of coffee rust, American leaf spot disease, and nematodes have been described earlier (Avelino et al., 2007, 2009, 2012).

2.1. Sampling and data collection

Data were obtained from two surveys (Avelino et al., 2007, 2009, 2012) conducted in five regions in Costa-Rica: Turrialba (53 plots), Western Valley (15 plots), Central Valley (14 plots), Tarrazú (13 plots) and Coto Brus (12 plots). Plots were monitored over one or two years. Because of unavoidable variation over years (e.g. climate, agricultural techniques and inputs), the successive production years in the same coffee plot were therefore considered as unique realisations of factors influencing the coffee agroecosystem, and thus, as separate statistical units (Avelino et al., 2007, 2009, 2012). As a result, a total of 141 statistical units, each corresponding to a production situation, were considered. A