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Landscape and crop management strategies to conserve pollination services and increase yields in tropical coffee farms

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ABSTRACT

Agricultural intensification has reduced biodiversity and leads to fundamental trade-offs between food production and conservation. Conventional approaches to food production are thus no longer suitable. In the present work, we discuss the influence of local management and landscape context variables on coffee yield and crop pollination services. We used 34 coffee farms (15 with low impact and 19 with high impact management) located in Chapada Diamantina, Bahia, Brazil. We analysed the floral visitor patterns and yield and their relationships with landscape and management context over two years. Using a GLM analysis, we found that farms close to natural areas and with low management intensity have higher potential to reduce yield gaps and maintain biodiversity. Biodiversity in turn (represented here by pollinators) improved yields by 30%, and yields were lower on larger, intensively managed farms. Low impact farms, on the other hand, may depend not only on diversified landscapes but also on proper investment in sustainable production practices. Combining landscape and management strategies should thus generate synergies between multiple ecosystem services, such as pollination, yield, farm profitability, and others not analysed here, such as natural enemies and nutrient cycling, among others.

1. Introduction

Global agricultural production was increased substantially by the introduction of new lands into continuous farming, the intensive use of off-farm inputs (fertilizers, pesticides, machinery), and the use of genetically modified crops, mostly after the "Green Revolution". However, new strategies to increase crop yields are needed to meet the current projections of global population growth. Moreover, the techniques utilized previously, such as intensive use of pesticides, have led to major losses in global biodiversity, leading to fundamental trade-offs between food production and conservation. Recent research demonstrates that conventional high input strategies are no longer suitable because the differences in crop yields between high and low-yielding farms in a given region (i.e., yield gaps) are increasing (Aizen et al., 2009). Yield gaps arise from multiple causes, including deficiencies in the supply of nutrients or pollination. Yet the ever-increasing input of nutrients and organic matter, or increases in cropping intensity and the expansion of irrigated area, are costly and may only bring about ever diminishing returns. Thus, researchers have been advised to focus on identifying the specific causes of yield gaps in order to develop sustainable and profitable alternatives to existing measures.

A new strategy to address the biodiversity-production trade-off is to optimize or improve crop yields at the same time as enhancing biodiversity, or at least minimize negative impacts, a paradigm also known as "ecological intensification". These strategies, however, are not so simple, because they require an understanding of complex relationships between the biological community composition and ecosystem function in contrasting management and landscape-level scenarios.

It has been suggested that trade-offs between food production and conservation areas are more likely to be alleviated through an optimal spatial arrangement (Fischer et al., 2008; Phalan et al., 2011; Gabriel et al., 2013; Hulme et al., 2013; Tuck et al., 2014; Ekroos et al., 2016). This could potentially include the combination of high-yield agriculture with areas of protected natural habitat (Ramankutty and Rhemtulla, 2012; Ekroos et al., 2016) or the integration of biodiversity conservation and crop production in the same area, such as in agroecosystems.

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There is no consensus yet for the best strategy. The best type of farming for biodiversity conservation seems to be dependent on the demand for agricultural products and how pollinator communities change with agricultural yield. The high chemical inputs of pesticides and nitrogen used to assure high yield on conventional farms leads to side effects, such as soil and water pollution (Potts et al., 2010; Foley et al., 2011). Agroecosystems, on the other hand, tend to present lower yields, requiring a larger land area for production.

Biodiversity and yield patterns are influenced not only by management and landscape context, including different spatial scales but also by the type of crop being grown and geographic region, further increasing the complexity of the relationship between crop production and conservation. Empirical studies linking landscape aspects, local management and ecosystem services are still scarce (Kremen, 2015), especially for some groups of species, such as pollinators.

Pollination is an example of an ecosystem service on which agricultural production is highly dependent, determining the yield in 75% of important global crop species. In coffee (*arabica* variety), although not considered a dependent crop since the plants are autogamous, pollinators can increase productivity (31% on average). Even so, despite its importance, pollination has been largely neglected in studies analysing yield gaps. Crops located far from natural areas, for example, may suffer losses in pollinators, stability, and production (Garibaldi et al., 2011b). However, to what extent this can be influenced by other landscape aspects such as patch diversity and crop management still requires further investigation.

In this study, we compared the influence of local management and landscape context variables on coffee yield and crop pollination services. We tested the following hypotheses using the approach described above: (i) floral visitor patterns and yields can be explained and influenced by differences in landscape and management context; and (ii) floral visitor composition also influenced coffee yields. We then examined what type of landscape-level scenario and management is the most suitable for biodiversity conservation and production purposes using coffee farms in Chapada Diamantina, Bahia, Brazil as a practical model.

2. Materials and methods

2.1. Study area and selection of sampling units

The present study was conducted on coffee farms located in the cities of Mucugê and Ibicoara in the Chapada Diamantina region, Bahia, Brazil (limits: 41°42′11” W, 12°43′36” S; 41°15′5” W, 12°43′52” S; 41°42′51” W, 13°44′8” S; 41°15′40” W, 13°44′ 23” S, altitude between 900 and 1400 m; Fig. 1). This region has an average annual precipitation of 1379 mm, an annual average maximum temperature of 25.7 °C, with a minimum temperature of 16 °C (2013 to 2014 local weather station data from the Landowners Association “Agropolo Mucuge/Ibicoara”; see Fig. A1 Appendix A). Chapada Diamantina, is dominated by the typical Brazilian Cerrado savannah, and shows a considerable variation in the physiological characters of the flora. This result in a mosaic of vegetation types, including from open meadows to semi-deciduous forests, with variable degrees of heterogeneity.

Using a geographic information system (GIS) with a SPOT image (year 2009, 5-m spatial resolution) and information about the region from field checks, we selected 34 sampling points. As criteria for this selection, we considered the surrounding proportion of cultivated area and landscape diversity, visually estimated from the image, with a buffer of 1.5 km around each sampling point. The distribution of sampling points within the study area followed an orthogonal gradient between the cultivated acreage and landscape diversity. A linear distance of 2 km was adopted as the minimum distance between sampling units (final minimum nearest neighbour distance = 2 km, mean = 22 km, maximum = 75.5 km; Fig. 1). These distances are consistent with the foraging range and dispersal distance of most Hymenoptera flower visitors and may be sufficient to minimize spatial pseudo replication (Greenleaf et al., 2007; Ricketts et al., 2008).

All sampling points corresponded to coffee farms that met our selection criteria (see below), and grew the same coffee variety (*Coffea arabica* variety Catucai). Farm management and characteristics were assessed through interviews at farms in a previous study. On the basis of these interviews, 19 of 34 farms were considered conventional farms with high impact management strategies, characterized by heavy use of pesticides. The remaining 15 farms were considered farms that used low impact management that supported “low input agriculture”, according to the definition of such by the Sustainable Agriculture Network (2010). This definition includes the low or non-existent use of pesticides and encompasses either certified organic farms lacking or having highly reduced the use of herbicides and fertilizers as well.

2.2. Flower visitor surveys

Following the method described by Vaissière et al. (2011), flower visitors were recorded in plots (50 × 25 m) located in the centre of small farms (up to 4 ha) and halfway between the centre and edge of medium and large farms (those larger than 5 ha) at each coffee farm in 2013 and 2014 (see Fig B1 Appendix B). The flower-visitor density was measured by visual scans, sampling a fixed number of open floral units (three to five open flowers in an inflorescence) inside the plots of each farm until 4000 floral units were reached (since the number of plants inside plots could vary according to the spacing used). The flower visitor species richness was measured by netting all visitors along four 25 m long transects for 5 min each. This resulted in 20 min of active net sampling per farm, with the clock stopped each time a captured insect was being handled.

Sampling was repeated at each coffee farm under sunny or cloudy conditions, but never during rain, and in at least two periods: morning (8:00 to 12:00) and afternoon (13:00 to 17:00) in the main flowering season (October to December). All visitors collected by net samplings were identified to the lowest possible taxonomic level by specialists and were deposited in the entomological collections of the Universidade Federal da Bahia (MZUFBA) and of the Instituto Nacional de Pesquisas da Amazônia (INPA).

Because the flower density may influence the attraction of flower visitors, we estimated the flower production at each farm by counting the number of flowers that were closed (buds), open, and old (no nectar or pollen present) on up to 20 inflorescences from different coffee plants (inside plots). From this, we estimated the total number of open flowers on each farm based on the size and plant spacing.

2.3. Yield gap

One to three days before flowering, 200 buds in pre-anthesis (one to eight buds per plant inside plots, on a total of 5000 flowers per treatment considering the 50 sampling points where we were able to perform this analysis) were assigned to one of the following treatments: (a) spontaneous self-pollination, where the bud was bagged with voile fabric bags (0.05 mm mesh size) to prevent insect flower visitors, and (b) open pollination, where the flower remained open to flower visitors. Bags were removed from the self-pollination treatment after 10–15 days when no more pollen transfer was possible and the risk of abortion caused by differences from light or temperature inside the voile bags could be minimized. Approximately six to seven months after flowering, marked coffee fruits were harvested. Yield gaps were calculated from the difference between the number of formed fruits in bagged versus unbagged flowers and extrapolated to the entire crop area (% formed fruits ha^{-1}). Information for extrapolation counts (number of open flowers, buds, and fruits) were gathered from the monitoring of 20 branches within 20 plants on each farm in both years. Counting was performed in at least two periods (when the bags were placed and at the harvest period). To account for the yield gap, we considered the final