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The contribution of non-managed social bees to coffee production: new economic insights based on farm-scale yield data

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Abstract Fruit set and quality of highland coffee (*Coffea arabica*) have been experimentally shown to be higher with bee-mediated or manual pollen supplementation than with autonomous self-pollination. Based on extrapolation from these small-scale experiments, very substantial monetary values for the pollination service have recently been suggested. However, previous research has not included direct measurement of coffee yield at a farm level in relation to pollinator activity, testing if pollinators are not only limiting fruit set and quality, but also coffee yield and farm profit. The extrapolations from small-scale experiments may be subject to error, because resource reallocation during fruit development, associated with enhanced pollination, was neglected, and many studies were restricted to a single coffee farm, limiting the validity of extrapolation. Here, we investigate the relationship between coffee yield and the community of coffee flower-visiting bees on 21 farms in Ecuador, where coffee is grown under tree shade. Our data show, for the first time on a farm-scale, that coffee yield was positively related to the density of non-managed, social flower-visiting bees per coffee shrub, but not to the number of inflorescences per shrub. Our data revealed that a fourfold increase in bee density was associated with an 80% increase in yield and an 800% increase in net revenues. Consequently, in our study higher yield associated with increased pollination generated higher revenues per hectare, so that farm profit was higher when bees were abundant.

Keywords *Coffea arabica* · Ecosystem service · Farm-wide yield · Honey bee · Pollination · Stingless bees

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Introduction

Bee pollination is an important ecosystem service for the maintenance of plant diversity, but also for successful fruit and seed set, and quality in many crops. Consequently, pollination service may contribute to the wellbeing of human society by enhancing quality and quantity of food and commercial products (Daily et al. 1997). Adequate pollination may be increasingly at risk, because agricultural intensification and the loss of habitats lead to an impoverishment of wild pollinators (Kremen et al. 2002). Insufficient pollination (pollen limitation) may result in yield reduction and thus economic disadvantages (Allen-Wardell et al. 1998). Therefore, there is urgent need for qualifying and quantifying pollination services in order to include them into local management practise for crop production (Daily et al. 1997).

The self-compatible highland coffee (*Coffea arabica*, Linné), an important cash crop in the tropics, was experimentally shown to benefit from bee pollination. Initial and final fruit set were found to increase due to bee-pollination or manual pollen supplementation, as a measurement of pollinator limitation (Ricketts et al. 2004), in comparison to autonomous self-pollination (Roubik 2002; Klein et al. 2003a). Furthermore, fruit weight and fruit shape increased through bee-mediated pollination (Roubik 2002; Ricketts et al. 2004; Olschewski et al. 2006). Some studies highlighted the importance of the naturalized non-native honey bee *Apis mellifera* (Linné) in the Neotropics (Roubik 2002), for example by experimentally placing hives into coffee plantations (Manrique and Thimann 2002). In contrast, other studies found a diverse, abundant community of coffee flower-visiting bees to provide high pollination services in coffee (Klein et al. 2003b; Ricketts et al. 2004). By extrapolating these enhancements in fruit set and quality, mainly derived from within-plant scale data, to yield, recently the monetary value of bee pollination for coffee production has been estimated (Ricketts et al. 2004; Olschewski et al. 2006).

However, albeit these experimental studies are inevitable for illuminating the functionality of bee visitation for fruit retention and development, they also may comprise limitations in their meaning, especially with respect to the economic conclusions to be drawn. Some of those studies restricted their analysis to initial fruit set (Klein et al. 2003a). But coffee is known to "overbear" by dropping a significant amount of initial fruits (Clifford and Wilson 1985), which changes final patterns at harvest (Bos et al. 2007). Furthermore the scale, at which pollination treatments, such as pollen supplementation, are conducted, influences the degree of measured pollen limitation (Knight et al. 2005). An increased fruit set due to pollen supplementation in only some flowers of a plant (as in most experiments) may exceed the controls, because of resource allocation among flowers, whereas the whole plant would be unable to respond with higher fruit set (Knight et al. 2005). Moreover, varying microclimatic conditions for plants in a coffee farm due to heterogeneous shading may affect fruit retention and development (Roubik 2002). However, the degree of shading of flowers was not included in the majority of fruit set experiments (but see Roubik 2002), although it is known to affect coffee production on a farm-wide scale (Perfecto et al. 2005). Ghazoul (2007) even claims that abiotic factors, which in turn determine pests or diseases, are more likely to limit yield on a farm-scale than the availability of pollinators. An additional problem of previous investigations is the restriction of studies to one single coffee farm (e.g. Manrique and Thieman 2002; Ricketts et al. 2004), thereby lacking general validity for a whole region. Taking into account these possible biases of small-scale experiments, extrapolations from fruit set data to quantify pollination services for crop production may lead to unrealistic conclusions, emphasizing the need for broad-scale investigations. Therefore, yield, measured at the farm-scale, as the ultimate outcome of pollination, is a more appropriate measure with which to evaluate pollination services for crop production.

Here, we measure coffee yield at the scale of 1 ha, including replication at the farm level, and then relate this to the whole community of naturally occurring pollinators. This allows us to complement previous experimental work by controlling for habitat conditions and management practices and test whether pollination services not only limit fruit and seed set, but also enhance crop yield at the farm scale and hence farmer's profits.

Materials and methods

Research sites

In the study region, Manabi, Ecuador (100–550 m asl, 17 N546800m, E9849274m), the highland coffee (Caturra variety) is cultivated in traditional, highly shaded agroforestry systems. Fertilizer or agrochemicals are not applied, and managed bee colonies are not used for pollination services. For our study we chose 21 agroforests of different smallholders, each about 1 ha in size. In this region conversion of forests to farmland took place more than one decade ago. Unfortunately no precise information could be provided on the respective age of the coffee stands, but all coffee farms were at least 5-years old. Coffee agroforests were embedded in a matrix of manifold habitats, such as agricultural system (rice paddies, pasture, maize fields) or bushland. Only few small forest fragments are left in this agriculturally dominated landscapes and their distance from the studied agroforests was too far (several kilometres) to act as a possible source of pollinators.

In the study region coffee flowers only once per year in the dry season, and flowering is limited to 1 or 2 days, with buds generally opening 8 days after a single heavy rainfall. In July/August in the following year (7–8 months after rainy season begins) fruits are completely ripened and are harvested. Coffee is being harvested by manually peeling of all berries on a branch at once (personal communication). As a further process, coffee berries are usually not cleaned but sold as dried fruits on the market (Olschewski et al. 2006). According to the owners, coffee harvest and processing was similar in all studied coffee farms.

Bee observations

From October to December (because different sites flowered at different times due to temporal variation in rainfall between areas) we observed wild coffee flower-visiting bees on four coffee shrubs per agroforest. We observed 15 min per shrub, recorded morphospecies and number of bee visits, which we hereafter name 'bee density'. We calculated the mean bee density per shrub of the four shrubs in a site. Because of the short flowering time phase (1/2 days) and because several sites flowered simultaneously, all observations were performed at only 1 day per site on the first day of flowering, when flowers were most attractive for visitors.

Yield and revenues

From July to August 2004 we quantified fresh coffee yield in kg ha^{-1} (Y_f) for each farm by weighing all harvested ripe fresh fruits of all bushes in one farm and dividing by the area of the farm. Since coffee prices and variable costs used to calculate revenues were based on dried coffee, fresh yields were divided by two to calculate dry fruit yield (Y_d). We then calculated net coffee revenue in US \$ ha^{-1} (R_n) using Eq. 1.:

$$R_n = 0.2\ Y_d - (0.07\ Y_d + 57)$$

where 0.2 is the long-term average price of \$0.2 (US) per kg and 57 is the fixed costs for pruning and cleaning of \$57 (US) per year and 0.07 the variable costs of \$0.07 (US) per kg for harvest and transport (Olschewski et al. 2006).

Parameters

We evaluated canopy cover, as an estimator of shade density, at the four edges and in the middle of nine 10 × 10 m quadrats (9 × 5 points = 45 points per site) using a densiometer (spherical crown densitometer, Forestry Suppliers). We calculated the density of coffee shrubs per hectare. To estimate the flower quantity per site, we calculated the mean number of inflorescences on four coffee shrubs, because each shrub in a site offered similar quantity of flowers due to similar age, and estimated the proportion of flowering coffee shrubs per site.

For five study sites information about soil characteristics was available (pH-value, carbon, nitrogen, phosphorus, sulphur (in mg/g dry soil), Na, K, Ca, Mg, Mn, Al, Fe, CIC = effective cation exchangeable capacity (as an indicator for fertility of soils) in milimol/kg dry soil). Yield (kg/ha) of fresh fruits was not related to any of the soil parameters (Lopez Ulloa unpublished data). Thus the effects of soil quality on yield were not examined further.

Statistics

We transformed variables to meet the assumptions of a normal distribution when necessary. Proportions were arcsin-square-root-transformed. To analyze relationships between yield or net revenues per hectare and the respective variables, we conducted multiple regressions with the software Statistica 6.1. (StatSoft 2003) and used backward selection until only significant variables remained.

Results

In total we observed 29 morphospecies of bees visiting coffee flowers in the 21 coffee farms, 19 species of social bees with 2,694 flower visitors, and 10 solitary bee species with only 29 flower visitors. The naturalized honeybee constituted between 10% and 67% of all observed flower visitors per site (mean 41.83% ± 19). Native bees (all bees excluding *Apis mellifera scutellata*, Lepeletier) made up between 25% and 90% of all observed flower-visiting bees (mean: 71.8% ± 18.6). The second most frequent visitor was a stingless bee species (*Partamona peckolti*, Friese), constituting from 1% to 50% of the bee individuals per site (mean 19.74% ± 17). Other repeatedly observed flower visitors were the stingless bee species *Nannotrigona mellaria*, Smith, *Nannotrigona perilampoides*, Cresson, *Cephalotrigona capitata*, Smith, *Tetragonisca angustula*, Latreille, *Trigona amalthea*, Vachal, and *Melipona mimetica*, Cockerell.

Coffee yield of fresh fruits was significantly positively correlated to mean bee density per coffee shrub (Fig. 1), but not to number of species of flower-visiting bees, canopy cover, coffee shrub density, mean number of inflorescences per shrub or the proportion of coffee shrubs flowering. Based on the regression equation we calculated that an increase from 20 to 80 in bee density was associated with a 78% increase in yield (80 bees: 1724.45 kg/ha, 20 bees: 970.4 kg/ha). Higher yield due to increased pollination services generated higher net revenues per hectare: By using Eq. 1 and the yield values calculated for 20 and 80 bees, divided by 2 to get weight for dried fruits, we estimated that a fourfold increase in bee density was even associated with an 816% increase in net revenues (80 bees: \$55.1 ha^{-1}, 20 bees: \$6 ha^{-1}, 95% confidence limits: −4.75, +41.1).

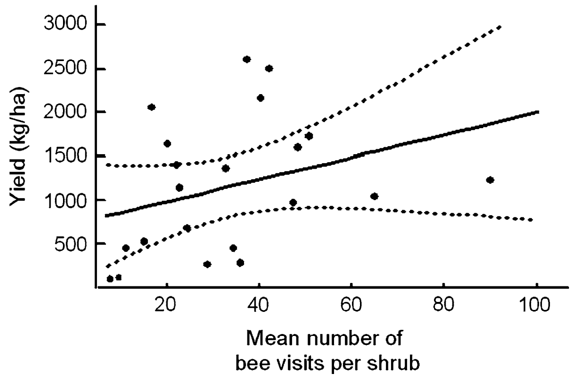

Fig. 1 Yield of fresh fruits (kg/ha) in relation to mean number of bee visits per shrub [$F_{1,19} = 4{,}7$, $r^2 = 0.20$, $P < 0.05$, $y = -659 + 1252.42 * \log(x)$; intercept coefficient: $P = 0.45$ (confidence limits: −2440,83, +1122,799), slope coefficient: $P < 0.05$ (confidence limits: +43,59, +2461,257)]. Full line represents the fitted yield-bee density relationship and dotted lines represent the 95% confidence intervals

Discussion

Our results, relating non-managed flower-visiting bees to farm-wide coffee yield, support previous experimental small-scale findings. By examining coffee production across 21 different independent coffee farms and controlling for soil, shade, plant variability, and processing practices we are able to show for the first time on a farm-scale the importance of coffee flower-visiting bees to coffee production, including naturalized honey bees and native bees. Yield (kg/ha) of 21 different coffee farms was linearly related to the density of bees. Our results display a 78% increase in yield with a fourfold increase in bee density.

The correlation between yield (kg/ha) and bee density is in accordance with previous small-scale work showing the contribution of bee pollination to fruit development by analyzing experimental treatments (Roubik 2002; Klein et al. 2003a). There are two potential causes why weight of all fruits per hectare increased with the number of bee visits on a coffee shrub. First, the quantity of developing fruits is higher in bee-pollinated flowers, and second, fruit weight is higher in bee pollinated than in passively self-pollinated flowers (Roubik 2002; Ricketts et al. 2004; Olschewski et al. 2006). Both enhancements, number of set fruits and fruit quality, can be ascribed to high pollination efficiency by bees, comprising outcrossing effects (Klein et al. 2003a), a more effective distribution of pollen by bees than by wind, and a highly efficient deposition of pollen on the stigma (Kremen et al. 2002; Ricketts 2004). Bees may also promote self-pollination; an increased fruit set through facilitated self-pollination could have already been shown by manually pollinating flowers with self pollen (Klein et al. 2003a). Yield was not related to the mean number of flowers per coffee shrub ($r = 0.32$, $P = 0.16$). Thus the positive relationship between yield and bee density indicates a higher number of developing fruits and weight of fruits due to a high density of pollinating bees. Consequently bee-mediated cross- and self-pollination complementarily increased yield, as already shown experimentally by Klein et al. (2003a).

We could not find any relationship between yield and bee species richness, such as observed by Klein et al. (2003b) between fruit set and bee species richness in Indonesia. In comparison to South East Asia, the neotropical community of coffee flower-visiting bees is dominated by a few, but abundant social bee species, the naturalized honeybee and stingless bee species (Roubik 2002; Ricketts 2004). In our study the naturalized honeybee accounted for more than 40% of individuals, and a second very abundant visitor was a stingless bee species. Other social bee species were relatively rare; we only found three to ten bee species per site. The supposedly efficient pollinating diverse community of solitary bee species (Klein et al. 2003b) was almost absent. Thus biodiversity effects in pollination were not found, and appeared to be negligible in the studied region.

Canopy cover had no effect on productivity of the studied coffee farms. Presumably the studied gradient was too small (between 80% and 100%) to reveal any effects on fruit development. However, in the model bee density only explained 20% of the variation in yield, 80% still remained unexplained in the regression. Factors which were not included in the analysis but are known to affect plant productivity, for example temporal climatic variation, or factors causing fruit abortion, such as drought, pests or diseases, nutritional resource limitations or the age of coffee stand (on which only vague information existed) might have had additional influence on yield. So far no study has managed to combine all abiotic and biotic parameters to determine coffee productivity in a single investigation to show the relative importance of each and their interactions with one another.

An increase in yield with bee density was associated with an increase in net revenues. Gains were greater at high bee densities than at low bee densities. According to our calculation, in this study a fourfold increase in bee density let to an 800% increase in net revenues. However, the net revenues of coffee production found in this study were rather low in comparison to other production areas of the world (Olschewski et al. 2007). To comply with the rules of organic coffee production farmers in the study region intensified their management (including cleaning and pruning), thereby generating higher costs. However, the produced coffee had not been recognized officially as ‘organic’, as quality has not reached a high standard yet. Consequently, selling prices were rather low.

From an economic point of view, our results confirmed previous estimations of the monetary value of pollination as an ecosystem service important for crop production (Ricketts et al. 2004; Olschewski et al. 2006). Those studies emphasised the economic relevance of pollinators for coffee production by estimating the monetary value of forest fragments as possible pollinator sources. In contrast, the farms included in this study were situated in a high impact area, with low incidence of forest fragments. Therefore our calculations of an augmentation in yield and income due to increased bee density apply for highly disturbed coffee growing regions, where nearby forest fragments as pollinator sources are not available. Management strategies to encourage pollination services by bees in highly disturbed landscapes should first focus on the habitat suitability of agroforests themselves. Measures, such as the conservation of old large trees as potential nesting sites, and flowering herbs, which bloom throughout the year, may encourage and conserve a high abundance of coffee flower-visiting bees for the coffee flowering season.

By assessing farm-scale yield of 21 different coffee farms, we complement previous small-scale experimental work examining the importance of bees for crop production. Although of correlative nature, our results may contribute to the recognition of the economic value of wild bee pollination to commercial crop production, thereby supporting conservation efforts to maintain these bees and the important ecosystem service they provide.

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