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Abstract

We investigate the role that economic instruments can play in the eradication of poverty and preservation of biodiversity in agroforestry management in coffee production. Most of the world's coffee producers live in poverty and manage agro-ecosystems in regions that culturally and biologically are among the most diverse on the globe. Despite the relatively recent finding that bees can augment pollination and boost coffee crop yields substantially, the short-term revenues to be had from intense monoculture drive land-use decisions that destroy forest strips serving as habitats for pollinating insects. Our study investigates the possibility of multiple equilibria in the adoption of technology in coffee production; farmers specialize in environmentally detrimental (sun-grown) or sustainable (shade-grown) farming or both practices co-exist. We calibrate an empirical model to characterize the equilibria and investigate the ecological and economic impacts of alternative policy instruments, among these protection fees, price premiums and a minimum wage.

Key words: Coffee, biodiversity, price premium, minimum wage, protection fee

JEL classification: D63, O1, Q56, Q57

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1 Introduction

The value of pollinators for commercial agriculture and the global ecosystem is widely recognized (see, e.g., Siebert, 1980, Olmstead and Wooten, 1987, Daily, 1997, Ricketts et al., 2004). Intense monoculture encouraged by high short-term returns of cash crops may lead to dramatic losses in yields in the long run due to decreased biodiversity and declines in pollinator populations. (Kevan and Phillips, 2001, Nunes et al., 2003) Indeed, it can be considered "unfair" that the benefits of biodiversity conservation accrue to both the local and global community, but the short-term costs are borne solely by the former. Management must rise to this challenge and accordingly fair trade arguments have been gaining ground. Yet, biodiversity conservation is rarely a major feature in international aid agreements aimed at alleviating poverty. (EU, 2005)

We investigate what role economic instruments can play in developing countries in preserving biodiversity while simultaneously aiming at the eradication of poverty. Our study incorporates scientific ecological findings on the role of pollination services into an economic analysis of agroforestry in coffee production. Coffee makes an interesting case as it ranks as one of the five most valuable export commodities (USD 7 billion in 2004) and coffee production employs about 25 million people worldwide (FAOSTAT, 2005, Ricketts et al., 2004). Over 70% of the world's coffee is produced by small-scale family farms. Most coffee producers live in poverty and manage agro-ecosystems in some of the world's most culturally and biologically diverse regions in Latin American, Asian, and African countries. (Bacon, 2005) Despite the increasing evidence that the abundance and diversity of bees can augment pollination and boost coffee crop yields in the long run (Roubik, 2002, Klein et al., 2003a,b,c), shade trees on plantations and forest strips near coffee farms are removed for the sake of greater short-term efficiency. The resulting loss of pollinator habitat is a considerable environmental problem worldwide (Kremen and Ricketts, 2000). Moreover, international coffee prices fluctuate substantially, for instance, due to occasional overproduction (Lewin et al., 2004, Perfecto et al., 2005). This worsens the situation of the impoverished farmers and may prompt the destruction of the remaining forest strips.

Some recent studies have drawn attention to the economic value of pollination services reflected as agroforestry benefits in coffee production systems; see, e.g., Ricketts et al. (2004). Gobbi (2000) finds that investment in biodiversity-friendly certification criteria is financially viable for coffee farms, while Benítez et al. (2006), Ninan and Sathyaplan (2005), and Olschewski et al. (2006) note that the high opportunity costs of land managed by ecological principles, in terms of lost benefits of intensely cultivated coffee or alternative crops, precipitates biodiversity degradation. An overall conclusion from these studies focusing on the value of pollination services is that policy measures such as trade-related standards, premiums, forms of tax relief, or dedicated government institutions are necessary for the adoption of biodiversity-friendly growing practices (see also Damodaran, 2002, Bacon, 2005, Perfecto et al., 2005).

Another strand of related literature has to a certain extent considered alternative policy instruments for protecting endangered natural ecosystems. For example, Ferraro and Simpson (2002) and Ferraro et al. (2005) find that direct methods such as conservation payments are more cost-efficient than indirect methods such as output and investment subsidies when policy programs aim to achieve large increments in biodiversity conservation areas. Interestingly, the empirical results of these case studies on apiculture in Madagascar may in fact hint at a possible reason for the popularity of indirect methods compared to the direct ones: the income in the recipient low-income nations rises considerably with even a small increase in the protection of rain forests through indirect means. Increased income is often the most important goal in many projects motivated by long-term sustainability and eradication of poverty (for an ongoing debate on this issue, see, e.g., Ferraro and Kiss 2002, Swart 2003). Eradication of poverty has not been considered explicitly in biodiversity studies. We investigate the performance of alternative economic instruments when there are two simultaneous goals — protection of biodiversity and elimination of poverty — and study whether direct methods can still be considered better policies given these two different objectives.

We augment previous policy analyses by modeling explicitly the ecosystem services provided by pollinators. To gain insights into the mechanisms that drive land allocation processes, the choice between environmentally detrimental and sustainable farming technology is determined in our model by the relative profits of the alternative technologies (cf., e.g., Bulte and Horan 2003). In our analysis, we focus on shade- and sun-grown coffee as alternative technologies; these are described in more detail in section 2. In particular, we study what drives land-use decisions when the economic optimization is carried out by several small farmers or a sole owner. Obviously, these two farm structures lead to different outcomes. We investigate the possibility of multiple equilibria in the adoption of technology: farmers specialize in either shade- or sun-grown coffee, or both practices co-exist. We examine under what circumstances the multiplicity actually occurs.

Finally, we investigate the impacts of three alternative policy tools on the choice of shade or sun coffee production: 1) price premiums, 2) conservation payments, and 3) a minimum wage. All of these instruments can be used for reducing environmental impoverishment but they work differently. Fair trade/eco-labeling is an example of a market-based conservation strategy where consumers pay a premium price for coffee produced on certified farms committed to preservation of biodiversity and fair working conditions (see, e.g., Perfecto et al., 2005, Swallow and Sedjo, 2000, Sedjo and Swallow, 2002). Conservation payments are an example of targeted aid, which is typically used for establishing protection areas (see, e.g., Ferraro and Simpson, 2002). A minimum wage represents a policy instrument designed for reducing inequality and preventing rural outmigration in developing countries (Lustig and McLeod, 1997, Gindling and Terrell, 2005, Lall et al., 2006). We study whether instruments aimed primarily at eliminating poverty (such as minimum wages) and, on the other hand, at protecting biodiversity (conservation payments) lead to conflicting outcomes when the input use intensity or production cost structure of alternative technologies differ. We compare these two specialized instruments to a third instrument in between the two, i.e., price premiums based on fair trade and eco-labels, which arguably target both poverty and biodiversity.

We calibrate an empirical model to describe land-use decisions at a representative local community level in Costa Rica. Commercial coffee production has been one of the most important factors in the economic development of the country and still is a major source of employment in rural areas. (Agne, 2000) Moreover, deforestation has traditionally been an important environmental problem in northern Latin America. Our empirical analysis facilitates a characterization of the alternative equilibria in land use and enables us to illustrate the magnitude of the ecological and economic impacts of the alternative policy measures.

Our study contributes to the previous literature by approaching the valuation of pollination services from a new angle. We recognize that maintaining environmentally sustainable farming practices requires a considerable allocation of resources to this technology to guarantee its existence. This is why the opportunity costs of conservation may become very high. Furthermore, trade-offs between the conservation of biodiversity and elimination of poverty should be taken into account when designing conservation policies. Our results indicate that a policy instrument explicitly designed for promoting economic (social) sustainability may turn out to conflict with the goals of conserving biodiversity and vice versa. Accordingly, the relative magnitude of these impacts is highly important information for those who actually make the coordinated decisions on policies to be adopted.

The rest of the paper is organized as follows. In section 2 we discuss the basic background concepts of this paper, namely, coffee production and its relation to pollination and biodiversity. In section 3 an analytic model is presented, and in section 4 it is applied to a specific case. Finally, section 5 provides some conclusions.

2 Coffee production, pollination, and biodiversity

In this section, we review the basic characteristics of coffee production, the importance of insect pollination to it, and the characteristics of the two production technologies discussed in this study. Rather than attempting to provide a comprehensive treatment of these issues, we concentrate on aspects that are relevant from the point of view of our analytic model and the empirical application. The main issues to be considered are that coffee can be produced using two alternative production methods and that the biodiversity and economic profitability implications of the production methods differ crucially from each other.

2.1 Coffee markets, production, and pollination

The demand for coffee has been fairly stable in recent years. However, the demand for certified fair trade and organic gourmet coffee has been growing fast, especially in the United States and the European Union, although their market share is still very small[1] (Bacon, 2005). On the other hand, supply fluctuates substantially, primarily due to weather conditions. This variation is exacerbated by the fact that coffee takes about three years from planting to harvest (one and a half years for hybrid variants), and thus the harvest area cannot be quickly altered to maintain a stable supply. In addition, coffee has a biannual production cycle, which further limits the possibility to adjust production to the market situation (Agne, 2000, Dicum and Luttinger, 1999). As a result, the average price of coffee has fluctuated fairly significantly.

Coffee production can be roughly analyzed in terms of two main methods.[2] The traditional method (hereafter 'shade coffee') is to grow coffee plants among shade trees, which may produce alternative products of economic value (e.g. fruits, medicine). This method involves relatively fewer coffee plants per hectare, relatively slower growth and smaller yield per plant, and a lesser need

[1] In 2005, the UK and Switzerland had achieved the largest market penetration of fair trade coffee in Europe, with the fair trade market shares being about 20% and 6% of all coffee, respectively. (FINE, 2005)In the world's largest coffee market, US, fair trade coffee accounts about 0.5%, but sales are growing at 50% annually, primarily for certified organic coffee. (Raynolds et al., 2004)

[2] Our rough division into sun and shade coffee is a simplification of the actual production technologies. For instance Moguel and Toledo (1999) divide coffee production systems in Mexico into five categories: *i*) rustic; *ii*) traditional polyculture; *iii*) commercial polyculture; *iv*) shaded monoculture; and *v*) unshaded monoculture. However, the two categories in our classification capture the essential economic and ecological differences of the alternative technologies for our purpose.

for commercial inputs. On the other hand, the method entails positive impacts on biodiversity and the soil as well as a relatively longer plant life span.

The second common method originated with the Green Revolution and involves growing coffee in the open without shade (hereafter 'sun coffee'). These plantations are *de facto* monocultures with intense production. The production method allows more coffee plants per hectare and produces a relatively quicker and higher yield per plant. However, it has negative impacts on biodiversity and soil, entails a shorter plant life span and imposes reliance on a single crop (coffee).

About two-thirds of the world's crop species include cultivars that require animal pollination and approximately one-third of food consumption in tropical countries originates from plants that are insect pollinated (Kremen et al., 2002, Ricketts et al., 2004). Two main coffee variants are used in production. The highland variety, *Coffea arabica*, is grown mainly in South and Central America and the lowland variety, *Coffea canephora* var. *robusta*, mainly in West Africa and Southeast Asia, although this geographical division has begun to disintegrate (Dicum and Luttinger, 1999).

C. arabica is self-pollinating, but it has been shown that cross-pollination by insects may increase the fruit set.[3] *C. canephora* is self-sterile and predominantly wind-pollinated, but also it has been shown to produce higher fruit sets when pollinated by both wind and insects. In addition, cross-pollination is likely to lead to larger and more robust fruit, increasing both the quality and the quantity of the crop. (Klein et al., 2003a,b,c, Ricketts et al., 2004, Roubik, 2002).

It has recently been shown that both the diversity and the abundance of bees that are important for pollination. Hence, biological diversity provides greater and more predictable pollination services, which in turn increases the fruit set (and thus the yield) of coffee plants. Bee diversity and abundance decrease with the distance to the nearest forest, whereby the fruit set (and hence yield) of coffee plants pollinated on open ground is reversely correlated with that distance. In order to maintain the pollination service provided by wild bee populations to coffee plants, the forest habitat of the bees needs to be conserved. (Klein et al., 2003b,c, Kremen et al., 2002, Ricketts et al., 2004, Steffan-Dewenter and Tscharntke, 1999)

[3] A fruit set is the number of fruits at harvest divided by the original number of flowers (Ricketts et al., 2004).

2.2 Implications for modeling

Given that sun coffee is intensively produced and generally hand pollinated, whether or not there are pollinating insects nearby is of little relevance. In contrast, insect pollination is important for shade coffee production. Accordingly, in our model the shade coffee system includes a forest strip serving as a pollinator habitat at the edge of the production area. We assume that the decisive factor in pollination is the distance to the nearest forest, not the existence of shade trees as such. This is captured by ecological parameters in our empirical application for Costa Rica (Ricketts et al., 2004). Thus, whereas the per hectare yield of sun coffee is assumed to be constant, the yield of shade coffee depends on the distance between the plantation and the nearest forest.

Certain other aspects of our empirical model require comment. First, price volatility is not accounted for in our deterministic analysis. The justification for this assumption is that as long as both prices (sun and shade coffee) move together, our results remain unaffected. Second, shade-coffee technology attracts a price premium on the international market, thus giving a higher producer price. It is worth noting that in practice the mere fact that one produces shade coffee does not provide any price premium. It is only when the production has been certified through some scheme that this benefit materializes. In this paper we assume an arbitrary certification scheme for shade coffee and that any costs of certification are already taken into account in the production costs. Third, shade-coffee production involves a higher production cost per hectare due to the need for more labor in production. Coffee production thus involves both economically and environmentally important dimensions. Accordingly, the two production technologies analyzed in this study have been chosen as differing in *i*) yield per hectare; *ii*) producer price per kilogram; *iii*) production costs per kilogram; *iv*) production costs per hectare; and *v*) dependence on forests and pollination.

3 The Model

In this section we first derive the profit functions of sun-coffee and shade-coffee technologies. Then we investigate two different farm structures: sole ownership and small-scale farms. Under sole ownership there is a single decision maker, who chooses an optimal land allocation between sun coffee and shade coffee. In the other setting, several small-scale farmers in the community make decisions between the two technologies. We do not consider how the small farms are actually situated and assume that the shape of the shade-coffee cultivation region is independent of individual farmers' actions. This makes it possible to formulate a static equilibrium model that need not take into account the process that would actually take place when farmers make their technology choices. Our focus is to describe the economic outcome of that process.

We let A denote the total area of land that is allocated to coffee production. The two technologies for coffee production, sun and shade coffee, are indexed by 1 and 2, respectively. The variable μ denotes the proportion of the area that is allocated to shade-coffee production. The proportion that is allocated for sun coffee is then $(1-\mu)$.

3.1 Yields and Profits

We assume that the yield of sun coffee depends only on the area which is allocated to its production. Hence, the effect of pollination on the yield is assumed to be negligible, which is in fact the case since, as mentioned earlier, the plants are pollinated manually. The yield is then simply $(1-\mu)Y_1A$, where Y_1 is the yield per hectare.

We divide the costs of producing coffee into two categories: costs that depend on the yield, e.g., harvesting and transportation costs (c_1), and costs that depend on the area of production, e.g., pest control and fertilization costs (e_1). Labor costs account for most of the area-dependent costs. When the per unit producer price of sun coffee is p_1, the profits are

$$\pi_1(\mu) = (p_1 - c_1)(1-\mu)Y_1A - e_1(1-\mu)A.$$

In the case of shade coffee, we assume that the yield depends on the distance of the coffee plant to the border of the pollinator source (forest), as shown by Klein et al. (2003c). We assume that the coffee plants form a continuous cover over the area in which they are grown; i.e., each point within the area produces some coffee.

Let x be the location of a point in the shade coffee plot and $d(x)$ its distance to pollinator source. We assume that the relationship between the distance and yield at the point is given by $\alpha - \beta\sqrt{d(x)}$ with the exception that the yield cannot fall below a certain minimum level $y_{\min}$. Hence, the yield at x is

$$y(x) = \max\{y_{\min}, \alpha - \beta\sqrt{d(x)}\}. \tag{1}$$

This model is based on the results of Klein et al. (2003c), who empirically determined the square-root relationship between the initial fruit set of a plant and the distance to the nearest forest. Assuming that yield is proportional to initial fruit set we obtain our formula for yield as a function of forest distance. In the Appendix, we compute the parameters α and β using the estimates given by Klein et al. (2003c).

We let $\mathcal{A}$ be the coordinates of the total plot with area A. We assume that the plot that is allocated to shade-coffee production has the same shape as $\mathcal{A}$. More specifically, the shape of the region in which shade coffee is produced remains unchanged but its size may vary as the allocation of area to shade-coffee production changes. This assumption makes it possible to do all the calculations using the original coordinates and to obtain the yield by scaling the results by factor μ. Hence, in computing the total yield we avoid having to define the location of the shade-coffee plot. In this section, the shape of the plot is arbitrary, but in section 4 we make our empirical computations assuming a circular area.

The pollinator source is the forest strip that surrounds the shade coffee plantation. In practice, the stretches of forest could form a more complex pattern depending on the landscape. Olschewski et al. (2006) have analyzed the economic impacts of bee pollination by assuming that the cultivated region surrounds the forest. In contrast, we assume that shade-coffee production has to include a forest strip, which is located at the edges of the cultivated area. The size of the forest depends on the area that is allocated to shade coffee. Specifically, a portion of the land allocated to shade-coffee production is covered by forest. We make a simplifying assumption that the forest strip has a fixed width, δ_0. Hence, for any given area of shade-coffee production the forest either covers a strip of width δ_0 or if the area is very small, the forest covers the whole area.

From now on we let $\delta(x)$ denote the distance of point x from the border of the entire area allocated to shade coffee, including the forest strip. In other words, $\delta(x) = d(x) + \delta_0$. As the shape of the region is invariant and its area is changed by a factor $\mu \in [0, 1]$, then those points within the original coordinates which satisfy $\delta(x) < \delta_0/\sqrt{\mu}$ belong to the forest strip whose size shrinks by the proportion of shade coffee area μ. Moreover, the minimum yield $y_{\min}$ is exceeded at points x, which satisfy

$$\delta_0/\sqrt{\mu} \leq \delta(x) \leq (\delta_u + \delta_0)/\sqrt{\mu}, \tag{2}$$

where $\delta_u = (\alpha - y_{\min})^2/\beta^2$. Here δ_u is the distance from the forest strip above in which the yield of a plant is $y_{\min}$; i.e., it is obtained from $y_{\min} = \alpha - \beta\sqrt{\delta_u}$.

By $\mathcal{A}(\mu)$ we denote those coordinates of the plot $\mathcal{A}$ that satisfy (2). Hence, those points in $\mathcal{A}$ that belong to $\mathcal{A}(\mu)$ produce coffee after reducing the area of the plot by the proportion μ. The yield of the reduced area is obtained by computing the yield of $\mathcal{A}(\mu)$ and then scaling it by μ. In brief, the idea is to compute the yield as if the whole region $\mathcal{A}$ were allocated to shade-coffee production and forest and then to scale the resulting yield to the level that corresponds to the reduced area.

The shrinking of the region and the crucial distances from the boundary of

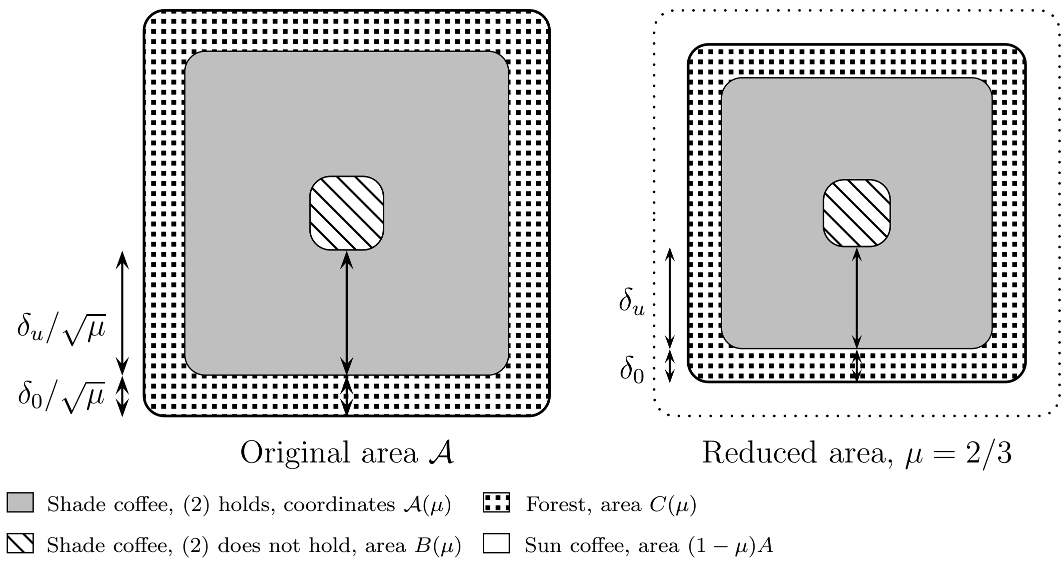

Figure 1. Illustration of reduction

the region are illustrated in Figure 1. Note that in Figure 1 the area on the right that is between the forest strip (dotted area) and the dotted boundary line is allocated for sun coffee. In the shaded area, the yield per plant is over $y_{\min}$ and in the center, $y_{\min}$.

The area of the region of $\mathcal{A}$ in which the yield per plant will be $y_{\min}$ after shrinking is denoted by $B(\mu)$ and the area of the region that will be the forest strip after shrinking is denoted by $C(\mu)$. As was done with the yield, these areas are computed using the original coordinates of $\mathcal{A}$, which means that they should be scaled by μ to obtain the correct areas after shrinking of the original region. Let $Y_{\min}$ denote the yield per hectare inside the region in which the yield per plant is $y_{\min}$. The total yield of shade coffee for a region that is obtained from $\mathcal{A}$ by shrinking it by the proportion μ is then

$$Y_2(\mu; \mathcal{A}) = \mu \int_{\mathcal{A}(\mu)} \left(\alpha - \beta\sqrt{\sqrt{\mu}\delta(x) - \delta_0}\right) dx + \mu B(\mu) Y_{\min}. \tag{3}$$

Recall from above that the yield of a plant located at x is $\alpha - \beta\sqrt{d(x)}$ and $d(x) = \delta(x) - \delta_0$. The proportion $\sqrt{\mu}$ in the integrand scales the integrand so that its maximum is α and minimum is $y_{\min}$. The factor μ outside the integral scales the result to the level that corresponds to the shrunken area. Recall that $\mathcal{A}(\mu)$ over which the integral is computed is a subset of the original coordinates $\mathcal{A}$ and that the resulting integral should therefore be scaled by μ.

The total profit of shade coffee is obtained by subtracting area-dependent costs from net returns of yield and adding the potential income from the forest strip:

$$\pi_2(\mu) = (p_2 - c_2)Y_2(\mu; \mathcal{A}) - e_2\mu[A - C(\mu)] + p_3\mu C(\mu), \tag{4}$$

where p_2 is the shade-coffee producer price, c_2 is the yield-proportional cost factor, e_2 is the area-proportional cost factor, and p_3 is the per hectare value obtained from the forest strip, for instance, a protection fee. In section 4.1 we shall study p_3 as a policy instrument; initially it is set to zero. Note that we do not explicitly allow the farmers to allocate their land to forest; rather the forest area always depends on the area allocated to shade coffee. However, as long as p_3 is reasonably low, whereby farmers would rather produce coffee than invest in forests, p_3 plays the role of a conservation payment rather than that of a subsidy paid to shade-coffee producers. Since the forest strip does not cause any costs, we subtract $C(\mu)$ from the total area in the second term of the sum in (4). We have excluded the possible extra profits from the products of shade trees in the profit function π_2. These products may include medicines, foods, construction materials and forage (Moguel and Toledo, 1999).[4]

In section 4.1 we study an empirical application where the area-dependent costs e_1 and e_2 are decomposed into labor costs and other costs. More specifically, the costs are assumed to be of the form

$$e_i = l_i w + z_i, \tag{5}$$

where $i \in \{1, 2\}$ and l_i is the amount of labor required for using technology i in person-months per hectare, w the wage in dollars per month, and z_i other area-dependent costs than labor costs.

The main difference between the profit functions π_1 and π_2 is that π_1 is linear in μ whereas π_2 is nonlinear. The linearity of π_1 means that there are constant returns to scale in sun-coffee production. On the other hand, the non-linearity in π_2 is solely due to non-linear pollination effects and all the other factors that could cause non-linearities are omitted. In practice, there could be economies of scale in coffee production or other factors causing additional non-linearities. Nevertheless, when these effects are reasonably small or they play the same role for both technologies, the linearity of π_1 is a justifiable approximation.

Note also that in our model there are no other factors than profits that drive the farmers' technology choices. In particular, we exclude risk attitudes from the analysis although coffee markets involve uncertainties; e.g., prices are volatile. Recall, however, from the previous section that since coffee plants

[4] We are not aware of explicit economic analyses being conducted on the value of coffee plantation shade tree products. In the case of cocoa plantations, a brief discussion of such products is provided by Rice and Greenberg (2000). If data were available, inclusion of such impacts in the analysis would present no difficulties.

are long lived, it is reasonable to assume that farmers make decisions according to long-run averages rather than adjusting their technology choices rapidly. Moreover, when the uncertain parameters of the two technologies behave in the same manner, their variability will not have a considerable effect on the equilibrium.

3.2 Equilibria and Joint Profits Maximum

We study two different farm structures: sole owner and small-scale farms. In the former setting, the land allocation decision between shade and sun coffee is made by maximizing the joint profits of the two technologies, i.e., $\pi_1(\mu) + \pi_2(\mu)$. In the latter setting, we assume that there is a large number of small-scale farmers who decide whether to belong to the community of sun- or shade-coffee farmers and that these farmers make their decisions without any coordination.

A sole owner allocates land to either of the two technologies by satisfying the first-order optimality condition $d\pi_1(\mu)/d\mu + d\pi_2(\mu)/d\mu = 0$, which can be written as

$$d\pi_2(\mu)/d\mu = A[(p_1 - c_1)Y_1 - e_1]. \qquad (6)$$

The right-hand side of (6) is the marginal profit from sun coffee, i.e., the marginal increase in profits for an increase in $(1-\mu)$. Geometrically, condition (6) means that the optimum is at the point where π_2 has a tangential line with slope $A[(p_1 - c_1)Y_1 - e_1]$. This is illustrated in Figure 2, where the dotted line is the tangent of π_2 at the joint profits maximum.

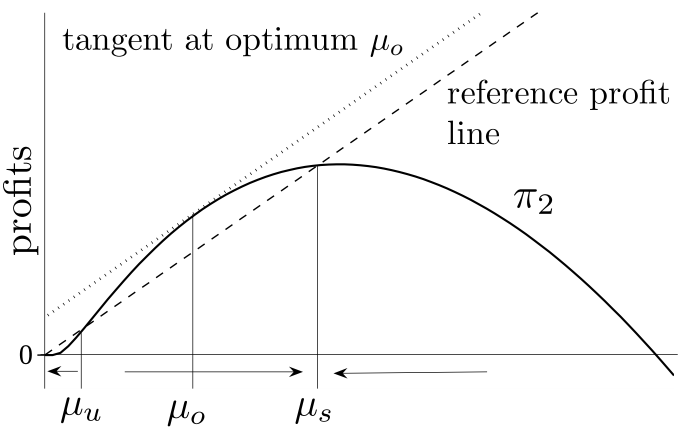

Figure 2. Illustration of π_2, the optimality and equilibrium conditions

Let us now discuss the small-scale farm setting. We assume that there are many farmers, whereby each farmer's marginal contribution to the profitability of the technology is negligible. The total profits from the technology chosen are shared in proportion to farm size. Thus, for a farmer whose land covers an area Δ of the community the profits from sun-coffee production will be $\Delta \times \pi_1(\mu)/[(1-\mu)A]$ and from shade-coffee production $\Delta \times \pi_2(\mu)/(\mu A)$. This means that the farmers' land allocation choices between the two technologies depend on the profitability of the technologies. Notice that in this model an individual farmer has to choose between the technologies and cannot allocate land to both sun and shade coffee. In practice, this means that the costs of having two production methods are prohibitively large for a small producer. Hence, an individual farmer faces a problem of technology choice rather than one of land allocation.

Since the farmers choose their production technology on the basis of profitability, an equilibrium is reached when the profitabilities are the same. Namely, if one of the technologies is more profitable, then at least some of the farmers will be willing to change technology. Profitability is measured as profits per hectare and the profitability factors are $\theta_1 = \pi_1/[(1-\mu)A] = (p_1 - c_1)Y_1 - e_1$ and $\theta_2 = \pi_2/(\mu A)$. At equilibrium, none of the farmers has an incentive to change from one technology to another, which means that $\theta_2 = \theta_1$. This condition can be written as

$$\pi_2(\mu) = \mu A[(p_1 - c_1)Y_1 - e_1] \tag{7}$$

and we shall refer to the right-hand side line of this condition, the line $\pi = \mu A[(p_1 - c_1)Y_1 - e_1]$, $\mu \in [0, 1]$, as the "reference profit" line because it gives the profit from sun-coffee production if a proportion μ of land area is allocated to sun coffee instead of shade coffee. Note that the slope of the reference profit line is the same as the right-hand side of (6). The difference between the two farm structures is that sole owner allocates land according to marginal profit whereas small-scale farmers choose the technology according to average profitability.

Assuming that the equilibrium μ^* is on the interval $(0, 1)$, we observe that the equilibrium profits $\pi_1(\mu^*) + \pi_2(\mu^*)$ are equal to the profits obtained when the whole area is allocated to sun coffee. This follows from the fact that shade coffee has the same profitability as sun coffee in equilibrium. Consequently, the total equilibrium profits are unaffected by the values of price p_2 and costs c_2 and e_2 as long as the equilibrium is on the interval $(0, 1)$. In particular, changing p_3 alters only the equilibrium allocation but not the total profits.

Let us now focus on the properties of the profit function of shade-coffee production, π_2. For a small enough μ, the corresponding profit $\pi_2(\mu)$ is zero because the whole area is covered by the forest strip; recall the assumption on the fixed width of the forest strip. Note that in equation (2) the lower bound for the distance after which the minimum yield is exceeded increases as μ decreases, which means that below a certain threshold level for μ there are no points that satisfy (2). The interpretation is that the entire area not in sun-coffee production is covered by forest. The profit π_2 starts to increase after the condition for the lower bound is met.

Depending on the parameter values, the marginal profit decreases for a large enough μ. The decreasing marginal profits follow from the fact that the proportion of the area in which the yield is $y_{\min}$ increases and the proportion of the area in which the pollination is effective decreases. Hence, as μ increases, a larger proportion of the yield comes from the area which is far from the forest. In particular, a larger proportion of the yield is produced in the region in which the yield per plant is $y_{\min}$. However, when shade-coffee production is extremely profitable, it may happen that the marginal profit increases along the entire interval $(0, 1)$ after the point at which π_2 becomes positive. Otherwise, there is a point after which the profit decreases, and π_2 is unimodal for μ over the threshold level after which it becomes positive. An example of such a profit function with diminishing marginal profits is provided in Figure 2, where the reference profit line is presented as a dashed line.

As seen in Figure 2, π_2 crosses the reference profit line twice. Hence, there are two equilibria, μ_u and μ_s, in the figure. On the interval (μ_u, μ_s) the profit function π_2 is above the reference profit line, which means that the profitability of shade coffee is greater than the profitability of sun coffee, i.e., $\theta_2 > \theta_1$. Assuming that the numerous small-scale farmers allocate their land to the technology that is the more profitable, there is a tendency to move towards the equilibrium μ_s when starting from an allocation where μ falls within the interval (μ_u, μ_s). For $\mu > \mu_s$ there is also a tendency to move towards μ_s, as sun coffee is the more profitable technology and the farmers shift from producing shade coffee to producing sun coffee, hence reducing μ. Thus, we can say that μ_s is a stable equilibrium. The other equilibrium, μ_u, is unstable by similar reasoning. We collect these observations to a remark below.

Remark 1. *There are at most two equilibria on the interval* $(0, 1)$*.*

1. *If there are two equilibria* $\mu_u < \mu_s$ *then* μ_s *is stable and* μ_u *is unstable.*
2. *If the equilibrium* μ^* *is unique in* $(0, 1)$*, it is unstable.*
3. *If there are no equilibria in* $(0, 1)$ *then shade-coffee production cannot be more profitable than sun-coffee production.*

If there is a unique equilibrium on the interval $(0, 1)$, then π_2 either crosses the reference profit line at one point or goes below it except for a tangential point; i.e., sun coffee is more profitable than shade coffee except at that point. In either case, π_2 goes below the reference profit line where μ is smaller than the equilibrium proportion. Hence, when starting from μ below the equilibrium farmers will decrease the land allocated to shade coffee. Therefore, this equilibrium is unstable. At the corners $\mu = 0$ or $\mu = 1$, one of the profitability factors cannot be defined. However, when π_2 goes below the reference profit line, we can say that there is no shade coffee at equilibrium since its production can never be more profitable than the production of sun coffee. Whenever there is a forest strip surrounding a shade coffee plantation, it is not possible that π_2 goes above the reference profit line for all $\mu \in (0,1)$, because, due to the forest strip, there is always an interval of μ where π_2 is zero. This leads us to our third observation in Remark 1. Recall that throughout this section we assume that $p_3 = 0$, which means that there are no economic gains from the forest strip.

We notice that when keeping the other parameters at their initial levels and changing only one of them, the stable equilibrium allocation μ increases in p_2, p_3, c_1, and e_1, and decreases in c_2, e_2, and p_1. In particular, the parameters p_2, p_3, c_1, and e_1 have lower bounds above which there is shade-coffee production in equilibrium. Similarly, c_2, e_2, and p_1 have upper bounds below which there is shade-coffee production in equilibria. When one of the parameters p_2, p_3, e_1, or c_1 becomes large enough, there is only one equilibrium on the interval $(0,1)$. This is because the stable equilibrium with a higher allocation for shade coffee converges to $\mu = 1$ as shade-coffee production becomes more profitable.

An example of a stable equilibrium as a function of p_2 is presented in Figure 3, where we see that below a certain threshold (the first dotted vertical line) there are no equilibria on the interval $(0,1)$ and hence all the area is allocated to sun coffee; see Remark 1. Above the other threshold level (the second dotted vertical line), the stable equilibrium coincides with $\mu = 1$ and all the area is allocated to shade coffee. Between these two lines the production technologies co-exist. The unstable equilibria as well as the joint profits maxima are also presented in the figure. At the lower threshold level, when the shade-coffee production becomes profitable, the two equilibria and the joint profits maximum coincide; i.e., there is a unique equilibrium which equals the joint profits maximum. This happens because there is only one equilibrium and at this point the line $\pi = \mu A[(p_1 - c_1)y_1 - e_1]$, $\mu \in (0,1)$, is tangential to π_2; see equations (6) and (7). In Remark 3 we shall show that it is a generic property of the model that the joint profits maximum is between the unstable and stable equilibria, as is the case in Figure 2.

In addition to stability, another criterion for selecting among the equilibria is dominance. We say that an equilibrium is dominant if the total profits $\pi_1 + \pi_2$ reach their maximum among all the equilibria at this equilibrium. We can make the following observations on dominance assuming that the extreme allocations $\mu = 0$ and $\mu = 1$ are equilibria. Indeed, when no land is allocated to one of the technologies, then its profitability is zero and there is no incentive to allocate any land to it.

Remark 2. *Let us consider $\mu = 0$ and $\mu = 1$ as possible equilibria.*

1. *When there are two equilibria $\mu_u < \mu_s$ on $(0,1)$, then μ_s is the dominant equilibrium.*

2. *When the equilibrium is unique on* $(0, 1)$ *and* π_2 *crosses the reference profit line, then* $\mu = 1$ *is the dominant equilibrium.*
3. *If* π_2 *is below the reference profit line, then* $\mu = 0$ *is the dominant equilibrium.*

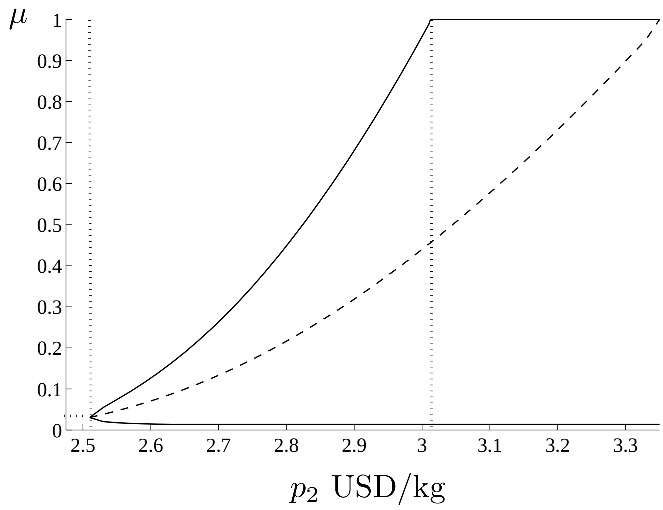

Figure 3. Illustration of equilibria and joint profits optimum (dashed line) as a function of p_2

The first part of Remark 2 holds because at μ_s the profits of shade-coffee production are always higher than at μ_u. In the second case, the highest total profits are obtained by allocating all the land to shade-coffee production. In the third case, the total profits are highest when the land is allocated to sun-coffee production. From remarks 1 and 2 we can note that when there are two equilibria on the interval $(0, 1)$, the higher of these is both stable and dominant. Therefore, in the following section we shall concentrate on the higher equilibrium whenever there are two equilibria on $(0, 1)$. If there is only one equilibrium on $(0, 1)$, we assume that $\mu = 1$ at the equilibrium as this equilibrium is dominant. When there are no equilibria on $(0, 1)$ we assume that $\mu = 0$ at equilibrium. Hence, the only case when there are two technologies in equilibrium in our analysis is the first case of remarks 1 and 2, when there are both stable and unstable equilibria. Otherwise, there is only one technology in equilibrium.

Finally, let us compare the dominant equilibrium with the outcome maximizing joint profits obtained under sole ownership. In Figure 2, the profit-maximizing point is where the line with slope $A[(p_1 - c_1)Y_1 - e_1]$ (the dotted line) is tangential to π_2. As stated in the following remark, this point can never be above the dominant equilibrium, which means that there will be more shade-coffee production in the equilibrium than would be optimal under sole ownership. The reason is that at the joint profits maximum shade coffee is more profitable than sun coffee, i.e., $\theta_2 > \theta_1$, although their marginal profits are the same. Small-scale farmers then have incentive to shift from sun-coffee production to shade coffee until the two technologies are equally profitable.

Remark 3. *The shade-coffee proportion that maximizes* $\pi_1 + \pi_2$ *does not exceed the dominant equilibrium allocation. When the dominated equilibrium is on the interval* $(0, 1)$ *the maximizing proportion is not below the dominated equilibrium allocation.*

If the dominant equilibrium is at $\mu = 0$, the total profits maximizing μ is also 0, as Remark 3 says. When the dominant equilibrium is reached at $\mu = 1$, the maximum can be at most at this point. Whenever, the dominant (and stable) equilibrium μ_s is reached on $(0, 1)$, it is obtained at a point at which marginal profits decrease; i.e., the curve π_2 goes above the reference profits line on $[\mu_u, \mu_s]$, where μ_u is the dominated (and unstable) equilibrium. Assuming that π_2 is continuously differentiable on (μ_u, μ_s), we have from the intermediate value theorem that there is a point on interval (μ_u, μ_s) at which the tangent of π_2 has the slope $A[(p_1 - c_1)Y_1 - e_1]$. At this point, the first-order condition (6) is satisfied and hence the shade-coffee proportion maximizing total profits is at most μ_s and at least μ_u.

Since our model involves a rather complex yield function presented in equation (3), it is difficult to solve the equilibrium and joint profits maximum analytically even when the shape of the cultivation region is simple, e.g., circular. In the following section, we analyze the model numerically to obtain more insight into its properties.

4 Empirical Application

In Costa Rica, the most important production area is Central Valley, where sun coffee is the predominant production method; shade-coffee production dominates in the surrounding areas of the valley (Agne, 2000). Ricketts et al. (2004) have attempted to estimate the economic value of bee habitat conservation to the coffee producers in this region. Within a single large farm they estimated that forest fragments provide pollination services worth USD $60,000$ annually. In order to provide some structure for our empirical application, we have adopted from the study by Ricketts et al. (2004) the production area, the forest area, and the yield and forest distance parameters used in calibrating our model. However, certain ecological relationships have been taken from studies conducted elsewhere. In our base scenario, we assume that the impact of pollination was only a higher fruit set and ignore impacts on berry weight as well as any possible quality improvements (see Olschewski et al. 2006). We carry out sensitivity analysis to check the robustness of our results regarding our assumptions on economic and ecological parameters. Hence, rather than providing exact figures, the purpose of this empirical application is to extract some stylized results from our model with parameter values that are as realistic as possible. Our main objectives are: *i*) to assess whether coexistence of both production types is possible, given the model specification used; *ii*) to assess to what extent the parameters used would need to be changed for a corner solution (of either sun or shade coffee); and *iii*) to assess the relative impacts of alternative policy instruments.

In our analysis, the total circular production area corresponds to the case of Ricketts et al. (2004), i.e., $1,256$ hectares (ha), which is the sum of $1,065$ ha and the area of the most significant forest patches surrounding the region under coffee cultivation (191 ha). We concentrate on bees as the providers of the pollination service, as they are important pollinators of both highland and lowland coffee.[5] Derivation of ecological parameters for the relationship between yield and distance to forest strip is thoroughly presented in the Appendix. All the yield parameters are summarized in Table 1. The production cost data in the analysis are assumed to be on the same scale as the costs in Table 6 of Kilian et al. (2004) for Costa Rican case farms. The price and cost parameters and their sources are presented in Table 2.

Table 1
Yield Parameters

Symbol	Value	Parameter	Source
A	1,256 ha	The total circular production area including forest	Ricketts et al. (2004)
Y_1	41 fa/ha	Yield of sun coffee	Kilian et al. (2004)
$Y_{\min}$	12 fa/ha	Minimum yield per hectare	Assumption
δ_0	158 m	Forest strip width	Obtained by assuming a circular forest strip of 191 ha as in Ricketts et al. (2004)
$y_{\min}$	0.0456 kg	Minimum yield in equation (1)	See Appendix
α	0.003 kg	Constant in equation (1)	See Appendix
β	4.44×10^{-4} kg/$\sqrt{m}$	Multiplier in equation (1)	See Appendix

4.1 Results

In this section, we compute numerically the dominant equilibrium (small-scale farming) and the joint profits maximum (sole ownership) for our empirical data. Our base scenario uses the parameter values presented in tables 1 and 2. For these values the dominant equilibrium is to allocate 90% of the area

[5] Costa Rica produces only *C. arabica*, as the production of *C. robusta* is prohibited by law (ICAFE website, 2006). Important pollinators of Costa Rican coffee flowers include the non-native feral African honeybees (*Apis mellifera*) and 10 native species of stingless bees. (Klein et al., 2003a, Kremen et al., 2002, Ricketts et al., 2004, Roubik, 2002)

Table 2
Price and Cost Parameters

Symbol	Value	Parameter	Source
c_1	USD 0.50 /kg	Yield dependent costs in sun-coffee production	Kilian et al. (2004), Ricketts et al. (2004)
c_2	USD 0.50 /kg	Yield dependent costs in shade-coffee production	Kilian et al. (2004), Ricketts et al. (2004)
e_1	USD 1,650 /ha	Area dependent costs in sun-coffee production	Kilian et al. (2004)
e_2	USD 2,090 /ha	Area dependent costs in shade-coffee production	Agne (2000), Kilian et al. (2004)
w	USD 142 /month	Minimum wage	U.S. Department of State, Bureau of Democracy, Human Rights, and Labor (2004)
l_1	month 3.14 /ha	Required labor in sun-coffee production	Obtained by assuming that 27% of e_1 is due to labor
l_2	month 3.27 /ha	Required labor in shade-coffee production	Obtained by assuming that 29% of e_2 is due to labor
z_1	USD 1205 /ha	Other than labor costs in sun-coffee production	Obtained by assuming that 73% of e_1 is other than labor costs
z_2	USD 1482 /ha	other than labor costs in sun-coffee production	Obtained by assuming that 71% of e_2 is other than labor costs
p_1	USD 1.39 /kg	Producer price of sun coffee	Kilian et al. (2004)
p_2	USD 2.98 /kg	Producer price of shade coffee	Kilian et al. (2004)
p_3	USD 0 /ha	Protection fee	Assumption

to shade-coffee production. The joint profits maximum that would maximize the total profits from the whole region is to allocate 41% of the area to shade coffee. This means that when the farmers do not coordinate their decisions, they allocate a considerable amount of land to the more profitable technology, which proves to be shade coffee, given our initial parameter values. The main characteristics of the dominant equilibrium (small-scale farming) and the joint profits maximum (sole ownership) are summarized in Table 3.

Table 3
Characteristics of dominant equilibria and joint optima for base scenario

Technology	Scenario	μ	Profits (USD)	(USD /ha)	Yield/ha
shade coffee	equilibrium	0.90	$32,200$	28.5	718 kg/ha (855 kg/ha)*
sun coffee	equilibrium	0.10	$3,600$	28.5	Y_1 (1,886 kg/ha)
shade coffee	optimum	0.41	$88,000$	169	715 kg/ha (930 kg/ha)*
sun coffee	optimum	0.59	$21,000$	28.5	Y_1

* yield/ha without the forest strip included

The size of the forest strip is 181 ha in the dominant equilibrium, and 120 ha in the joint profits maximum. In the dominant equilibrium the profitability of the two technologies is the same, whereas in the joint profits maximum the profitability of shade coffee is much higher than that of sun coffee. The most striking difference is in the total profits, which are about USD $35,800$ in the dominant equilibrium and USD $109,000$ in the joint profits maximum. This is an interesting result. There seems to be a clear incentive for the small-scale farmers to coordinate their land allocation decisions to maximize their total economic benefits. Obviously, this would lead to a further decrease in land area for shade coffee, down to 41 percent according to our analysis. This would be a dramatic decrease, as historically only shade coffee has been cultivated. The dilemma for policy makers is that maximizing joint profits would be an efficient way to increase economic benefits and alleviate poverty. However, there are most likely additional environmental benefits from having more shade-coffee production than a profit-maximizing optimum would provide. As there is not enough scientific knowledge for determining an ecologically optimal amount of shade coffee production, we compare the impacts of alternative policy instruments designed for promoting ecologically and economically sustainable farming practices. In the following, we will mainly focus on the impacts on the dominant equilibrium if the results for the joint profits maximum do not differ fundamentally.

4.1.1 Price premiums and cost margins

The results in the base scenario were computed for a price premium of USD 1.59 /kg, i.e., the price of shade coffee being 115% higher than that of sun coffee according to our price data. It is illustrative to compute a minimum price that would guarantee production of shade coffee. The threshold for the price p_2 below which there is no shade-coffee production in the dominant equilibrium is about USD 2.51 /kg; more importantly, the price margin $p_2 - p_1$ should be at least USD 1.12 /kg. This means that the price of shade coffee should be about 80% higher than the price of sun coffee. The threshold for p_2 above which there is only shade coffee in the dominant equilibrium is about USD 3.01 /kg, i.e.; $p_2 - p_1$ should be at least USD 1.62 /kg. The upper and lower thresholds are illustrated as dotted vertical lines in Figure 3, where the equilibrium as well as the joint profits maximum are illustrated as a function of p_2. Recall from section 3.2 that the lower thresholds are the same for equilibria and the joint profits maximum, because when the shade-coffee production becomes profitable there is only one equilibrium and this equilibrium is also the joint profit optimum. For our given initial prices and price premium in the base scenario, we can naturally obtain also threshold levels for the cost c_2 and the cost margin $c_2 - c_1$ The cost of shade coffee, c_2, should not increase above USD 0.97 /kg; i.e., the cost margin should not exceed USD 0.47 /kg while prices stay at their initial levels (Table 2).

Our results suggest that premiums should be quite substantial to attract farmers to maintain their shade coffee production systems. Some studies indicate that certain consumer segments are willing to pay such high premiums, but it is not likely to hold true for all consumers of coffee. (CEC 2001, Loureiro and Lotade 2005) The actual premiums paid for sustainable coffees by industry have been about USD 1.32 per kg. (Giovannucci, 2001)

4.1.2 Protection fees

It can be expected, of course, that introducing a protection fee (p_3) would increase the production area of shade coffee. For a protection fee of USD 100 /ha, the allocation of shade coffee in the dominant equilibrium increases about 7%. The proportion of shade coffee in the joint profits maximum increases only slowly as a function of the protection fee because of the low profitability of shade coffee for large μ. For example, without the protection fee π_2 decreases for $\mu \geq 0.46$.

According to Ricketts et al. (2004), the Costa Rican Environmental Service Payments Program subsidizes the conservation of forests by USD 42/ha within their study area. Such a subsidy would increase forest area by 1.6%, which is a negligible impact compared to the cost; each hectare of forest in addition to 181 ha in the base scenario equilibrium costs USD $2,700$. Naturally, if the forests are valued for benefits other than the pollination service, such a payment may be warranted, but it is worth noting that according to our analysis it would not be sufficient to alter the relative profitability of sun and shade coffee in any significant way. Recall from section 3.2 that the total equilibrium profits are unaffected by the choice of p_3.

4.1.3 Minimum wage

In Costa Rica the state sets the minimum wage, and in 2003 the monthly minimum wage was USD 142 (U.S. Department of State, Bureau of Democracy, Human Rights, and Labor, 2004), which we assume to be the minimum wage for farm workers.[6] We divided the area-dependent costs e_1 and e_2 into labor costs and other costs, as was shown in equation (5). Assuming that the labor costs consist of wages only, we estimated labor costs for shade and sun coffee from Table 6 of Kilian et al. (2004) to analyze the effect of minimum wages on the equilibrium allocation of land (see Table 4). Since shade-coffee production is more labor intensive, the amount of land allocated to it decreases as the minimum wage increases. A minimum wage increase of USD 100 (71%), i.e., from USD 142 to USD 242, would decrease the proportion of shade-coffee land area by about 17% in the dominant equilibrium. Due to the similar linear structure of costs of labor both in shade and sun coffee production, a substantial increase in the minimum wage would not make the shade coffee production area decrease in the same proportion, or equally dramatically. However, the economic impacts of such an increase in wages might be significant. These impacts will be considered further in the following to facilitate a better com-

[6] Note that the highest minimum wage in Costa Rica is for university graduates, USD 560/month. According to an ILO database, in 2003 non-qualified workers in the agricultural sector received about USD 9.1/day, or a maximum of about USD 182/month.

parison of the alternative policy instruments targeting sustainability of coffee production.

4.1.4 Comparison of instruments

In Figure 4, the left part illustrates the price of shade coffee that is required to maintain the equilibrium and joint profits optimum at the initial levels when the minimum wage increases from USD 142 /month. On the right in Figure 4, we see the required protection fee for keeping the land allocations at their original levels as the minimum wage increases.

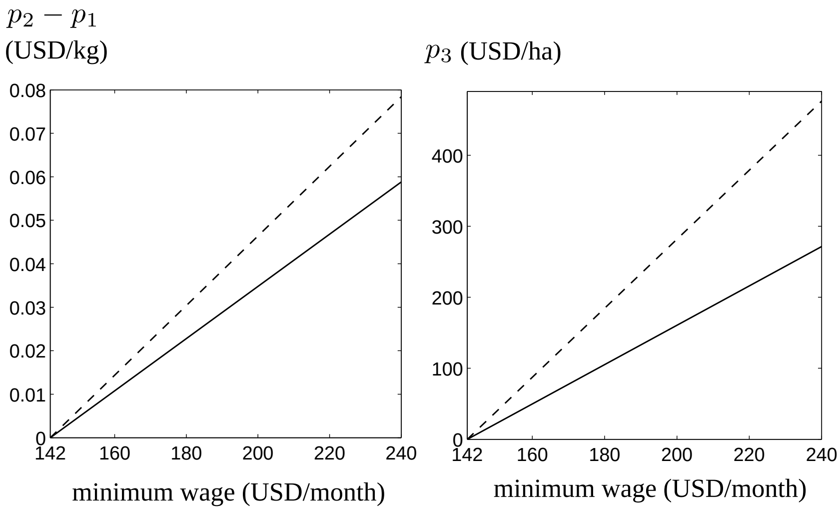

Figure 4. Shade-coffee price and protection fee for equilibrium and joint profits optimum (dashed lines)

For an increase of USD 100 in the minimum wage, the protection fee to compensate for the effect of the higher wage is about USD 277 /ha for the dominant equilibrium (small-scale farming) and about USD 486 /ha for the joint profits maximum (sole ownership); these are reasonably high figures. It should also be noted that the corresponding increases required for the price premiums would be USD 0.06 /kg (2.1%) for the dominant equilibrium and USD 0.08 /kg (2.7%) for the joint profits maximum. These comparisons suggest that the importance of a choice of a policy instrument should not be underestimated. Therefore, we make further comparisons on the ecological and economic impacts of the alternative instruments.

To make the instruments comparable, we fix the budget expenditure that is going to be used for promoting sustainable farming practices. Any arbitrary sum of money could be chosen for comparison, and we assume that a donor spends USD 10 /ha for the total production area under consideration (or a lump sum of USD $12,560 = 10$ /ha $\times 1,256$ha). Table 4 summarizes the impacts of alternative policy instruments on the proportion of shade-coffee production, μ, and

Table 4
Comparison of policy impacts when an additional payment of USD 10 /ha is delivered through alternative policy instruments

Instrument	Minimum wage	Protection fee	Price premium
Value (change)	USD 145 /month (+2.1%)	USD 44 /forest ha	USD 1.60 /kg (+0.8%)
μ (change)	0.89 (−0.9%)	0.92 (+3.1%)	0.94 (+4.2%)
Forest area (change)	180 ha (−0.4%)	184 ha (+1.6%)	185 ha (+2.2%)
Profits (USD) (change)	35,900* (+0.2%)	35,800 (±0%)	35,800 (±0%)
Wage sum (USD) (change)	644,000 (+2.0%)	636,000 (+0.6%)	637,000 (+0.8%)

* USD 10 /ha added to profits

forest area in the dominant equilibrium. The largest increase in shade-coffee production (4.2%) and forest area (2.2%) would be achieved by increasing the price premium (by about 1.3 US cents/kg, or about 0.8%). In contrast, if the same amount of funding were spent on compensating for additional input cost, or an increase in the wage rate for poor employees, the minimum wage could be increased by 2% with only a negligible negative impact on forest preservation. Allocating funding through a protection fee (USD 44) would increase both shade-coffee (3.0%) and forest (1.5%) area.

A comparison of economic impacts reveals how poverty would be impacted by the alternative instruments. Social benefits measured by a wage sum would favor the increase of the minimum wage as a policy instrument for the alleviation of poverty. This would come at the expense of ecological benefits, leading to a reduction in the forest area in contrast to the other instruments. These figures illuminate the tension between the conflicting outcomes of using these instruments. In achieving the highest positive ecological impacts, or an increase of 2% in forest area, and simultaneously yielding an increase in the wage sum, the price premium would be preferable as an instrument to a protection fee. However, when comparing the price premium to the minimum wage, the additional forest area of 4.7 ha would be attained by a decrease in the wage sum of USD $7,250$ such that the value of an extra hectare forest would be USD $1,533$ in terms of lost wages.

4.2 Sensitivity Analysis

The previous sections showed the sensitivity of our results to the economic parameters used. As there are many uncertainties related to the ecological data, we carry out sensitivity analysis for selected key parameters of our model to see whether the results are driven by the underlying assumptions concerning ecology. We study the effects of the minimum width of the forest strip (δ_0), and the yield of sun coffee (Y_1).

As the forest strip surrounding the shade-coffee region becomes wider, the equilibrium allocation and the joint profits maximum of shade coffee decreases. When δ_0 is less than 125 m, there is only shade coffee in the equilibrium. Doubling the width from 125 m to 250 m would decrease the land allocated to shade coffee by 34% from $\mu = 1$ to $\mu = 0.66$. The joint profits maximum is less sensitive to the choice of δ_0. Increasing the width from 125 m to 250 m decreases the optimal μ to from 0.45 to 0.33, i.e., the decrease is 27%. At the limit, when δ_0 tends to zero, the joint profits maximum is reached at $\mu = 0.6$, which is thus the upper bound of optimal μ for any δ_0.

Finally, let us discuss the effect of the yield of the sun coffee, Y_1. The relationship between the critical price thresholds and Y_1 is linear. For a one-hundred kilogram increase in minimum yield per hectare the change in the price thresholds is USD 0.125, i.e., if Y_1 is increased by 100 kg/ha the resulting increase in the price premium above which there is only shade coffee is USD 0.125; The threshold below which there is only sun coffee behaves approximately the same way, which is also the case for the equilibrium. If yields could be increased in sun coffee production, for instance, by 10%, the price premium for shade coffee should increase about 23%

The most interesting finding from the parameters above is the width of forest strip required for pollinator habitats, as it clearly affects the attractiveness of shade coffee production. The sensitivity analysis also suggests that one should be careful to not draw excessively straightforward conclusions on the absolute impacts of policies suggested by the data. However, a comparison of relative impacts is plausible.

5 Conclusions

Overuse of natural resources may be a direct consequence of poverty, given that a choice of farming practices typically involves a trade off between short-term private benefits and a public good, biodiversity, or long-term sustainability in land use. By capturing the interaction between coffee yield and pollination services in an analytical bio-economic model, we have investigated the decline in biodiversity related to two alternative production methods, sun- and shade-grown coffee.

We examined the pattern of technology choice at a representative local community level by calibrating an empirical model using data from Costa Rica. We found that maintaining environmentally sustainable farming practices requires over-allocation of land to shade-coffee production compared to levels that would be economically optimal. This results from an inability to coordinate management decisions when there are several economic agents, typically small-scale farmers, involved. We assumed that the small-scale farmers choose between shade and sun coffee based on the profitability of each technology. This leads to a dominant equilibrium where the profitability of each technology is the same whereas in an economic optimum the marginal profits are equalized. In the dominant equilibrium, a smaller area of shade coffee would produce higher profits per hectare due to a better pollination effect. Following Klein et al. (2003c), we assumed that the yield of a plant decreases as a function of distance to the forest surrounding the shade-coffee region. For a larger area of shade coffee, more plants are far away from the forest serving as the source of pollinating bees. This explains why in the dominant equilibrium allocating less land to shade coffee would increase the total profits and why the opportunity costs of shade-coffee production are high.

Furthermore, we compared alternative policy instruments — price premiums, protection fees, and minimum wages — and investigated whether it is possible to prevent loss of biodiversity and alleviate poverty simultaneously. Somewhat surprisingly, a direct protection fee was outperformed by a price premium for achieving comparable positive economic and ecological impacts. However, our results suggest that fetching price premiums high enough for shade coffee may be a challenge. Moreover, we expected a priori that increasing minimum wages would increase the relative profitability of sun-coffee production at the expense of shade coffee, given that production of shade coffee is more labor intensive. However, we found this impact negligible in our analysis, and an increase in minimum wages could in fact be a stabilizing, robust policy instrument. It would not lead to a dramatic decrease in the forest area, and the positive economic impacts would be significant. A policy recommendation would then be that addressing poverty first could help conserve biodiversity.

6 Appendix

We derive a relationship between yield and distance to a forest strip, or parameters α and β of section 3.1. Klein et al. (2003c) have presented the regression model below for the fruit-set percentage of *C. canephora*[7]:

$$s = a - b\sqrt{d}, \tag{8}$$

where s is the fruit-set percentage of a coffee plant and d is its distance to pollinator source, i.e., the distance to forest with parameter values $a = 94.11$

[7] Although the relationship is for *C. canephora*, and we deal with *C. arabica*, we justify the decision to use the relationship by the fact that we are not aware of such a relationship being available for *C. arabica*. Moreover, Olschewski et al. (2006) reason that the ecological mechanisms for coffee pollination services and coffee berry borer infestation are similar in different regions.

and $b = 1.15$. A similar regression model for forest distance and berry weight has been considered by Olschewski et al. (2006). Let us assume that the fruit-set percentage, s, and the yield of a coffee plant, y, have the relationship $y = \bar{a} + \bar{b}s$ [8]. The two unknowns $\bar{a}$ and $\bar{b}$ can be solved for by taking two observations (y_n, s_n) and (y_f, s_f) close to and far from the pollinator source, respectively.

According to Ricketts et al. (2004), the average yield for *C. arabica* is $\tilde{y}_n = 21.5$ fa/ha in an area that is within one kilometer of the pollinator source. One fanegas (fa) amounts to 255 kg of fresh coffee and 46 kg of green coffee; see Lyngbæk et al. (2001). Beyond one kilometer, the average yield is $\tilde{y}_f = 17.8$ fa/ha. Assuming that there are 1500 coffee plants in one hectare (Rice and Ward (1996)), we obtain the estimates y_n and y_f given in Table 5. We assume that y_f is the yield at the distance $d_f = 1,000$ m and that y_n is an unknown variable. In the experiments of Ricketts et al. (2004), the pollination services of bees farther than $1,400$ m from the forest were inadequate. Furthermore, Ricketts (2004) observes that plants farther than 300 m from forest rely almost exclusively on pollination by *Apis mellifera*. The fruit-set percentages s_n and s_f corresponding to the two distances d_n and d_f can be computed from (8). The values of parameters $\bar{a}$ and $\bar{b}$ are then

$$\bar{a} = (s_f y_n - s_n y_f)/(s_f - s_n) \text{ and } \bar{b} = (y_f - y_n)/(s_f - s_n). \tag{9}$$

The next step is to construct the yield as a function of distance from the pollinator source. From Klein et al. (2003c) and our assumption on a linear relationship between yield and fruit set (see the discussion in section 3.1), we have $y(x) = \min\{\tilde{y}_{\min}, \tilde{\alpha} - \tilde{\beta}\sqrt{d(x)}\}$, where $\tilde{y}_{\min}$ is the minimum yield of a plant (see Table) and

$$\tilde{\alpha} = \bar{a} + \bar{b}a \text{ and } \tilde{\beta} = b\bar{b}. \tag{10}$$

The above yield model is for a coffee plant, whereas we are interested in obtaining the parameters for infinitesimal pieces of land, over which we can then integrate to obtain the yield. Hence, we need to calibrate our model such that function (3) produces a realistic yield. The calibration can be done by scaling $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ so that the area of 1065 ha ($A(1)+B(1)$ in (3) for $\mu = 1$) produces $20 \times 1,065$ fa; see Ricketts et al. (2004), who have estimated that 20 fa/ha is the mean yield of their case farm.

In principle, the choice of d_n determines what the final parameters are. The proper choice is obtained by requiring that the average yield within one kilometer of the pollination source be 21.5 fa/ha as in Ricketts et al. (2004). In

[8] In addition to fruit set, effective pollination enhances fruit mass Ricketts et al. (2004). We do not consider the effect of forest distance to fruit mass.

practice, d_n can be found iteratively by solving for the scaling factor ρ and the parameters $\tilde{\alpha}$, $\tilde{\beta}$, and $y_{\min}$ for a given d_n and then decreasing or increasing the factor depending on whether the resulting average yield within a kilometer of forest is more or less than 21.5 fa/ha. We obtain $d_n = 579.4$ m.

By taking $Y_{\min} = 12$ fa/ha as the minimum yield for the region far from the forest, we get the scaling factor $\rho = 0.136$. The final parameters are then obtained by multiplying $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ by this factor; i.e., the parameters α, β, and $y_{\min}$ appearing in section 3.1 are $\alpha = \rho\tilde{\alpha}$, $\beta = \rho\tilde{\beta}$, and $y_{\min} = \rho\tilde{y}_{\min}$. All the calibration parameters are collected in Table 5.

Table 5
Model Calibration Parameters

a	94.11 %	Intersect in equation determining shade coffee fruit set as a function of forest distance	Klein et al. (2003c)
b	1.15	Distance coefficient in equation determining shade-coffee fruit set as a function of forest distance	Klein et al. (2003c)
s_f	57.7 %	Fruit set percentage far from the forest	Obtained from (8) at $d = 1000$
$\tilde{\alpha}$	0.0222 $\frac{\text{fa}}{\text{plant}}$	Intersect in equation determining shade-coffee yield as a function of forest distance	Obtained from (10)
$\tilde{\beta}$	3.26×10^{-4}	Distance coefficient in equation determining shade-coffee yield as a function of forest distance	Obtained from (10)
$\tilde{y}_{\min}$	0.008 $\frac{\text{fa}}{\text{plant}}$	Minimum yield per plant	$Y_{\min}$/(1500 plant/ha)
ρ	0.141	Scaling factor for $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ to obtain final values	Obtained from requiring the yield of 1,065 ha region to be 20×1,065 fa

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