Appendices

A.1 Yield of shade coffee

We assume that 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 from the 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

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

The total yield is obtained by integrating $y(x)$ over the coordinates of the shade coffee region. We assume that the shape of the shade coffee region remains unchanged but that its size may vary as the allocation of area to shade coffee production changes. This assumption makes it possible to do all the calculations as if the whole region were allocated for shade coffee and then to scale the resulting yield by factor μ. Hence, in computing the total yield we avoid having to define the location of the shade coffee plot. In the computation we need only take care of the integration limits. This is explained below where we derive the yield function for an area of arbitrary shape.

The shade coffee region is surrounded by a forest strip with a fixed width, δ_0. In other words, 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, $\delta(x) = d(x) + \delta_0$.

Let $\mathcal{A}$ denote the coordinates of the entire region with area A. 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 $\mathcal{A}$ which satisfy $\delta(x) < \delta_0/\sqrt{\mu}$ belong to the forest strip of the reduced shade coffee region. The shrinking of the region and the crucial distances from the boundary of the region are illustrated in Figure A.1. Note that in Figure A.1 the area on the right 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 that will be the forest strip after reduction in shade coffee area is denoted by $C(\mu)$. The minimum yield $y_{\min}$ is exceeded at points x, which satisfy

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

where $\delta_u = (\alpha - y_{\min})^2/\beta^2$. Here δ_u is the distance from the forest strip above which the yield obtained at a point is $y_{\min}$; i.e., δ_u is solved from $y_{\min} = \alpha - \beta\sqrt{\delta_u}$. In the following, $\mathcal{A}(\mu)$ is the set of those coordinates of the plot $\mathcal{A}$ that satisfy (A.2) and $B(\mu)$ is the size of the area of $\mathcal{A}$ in which the yield at each point is $y_{\min}$ after reduction. Moreover, $Y_{\min}$ denotes the yield per hectare inside the region where the yield at each point is $y_{\min}$. The yield of the reduced area is obtained by computing the yield over $\mathcal{A}(\mu)$, adding $Y_{\min}B(\mu)$ to this, and then scaling the result by μ. The same scaling is done in the calculation of the forest area. The total yield of shade coffee for a region that is obtained from $\mathcal{A}$ by shrinking it by the proportion μ is then

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

Recall that the yield at x is $\alpha - \beta\sqrt{d(x)}$ and $d(x) = \delta(x) - \delta_0$. The factor $\sqrt{\mu}$ in the integrand scales it such that its maximum is α and minimum is $y_{\min}$. The factor μ outside the integral scales the result to the level corresponding to the shrunken area.

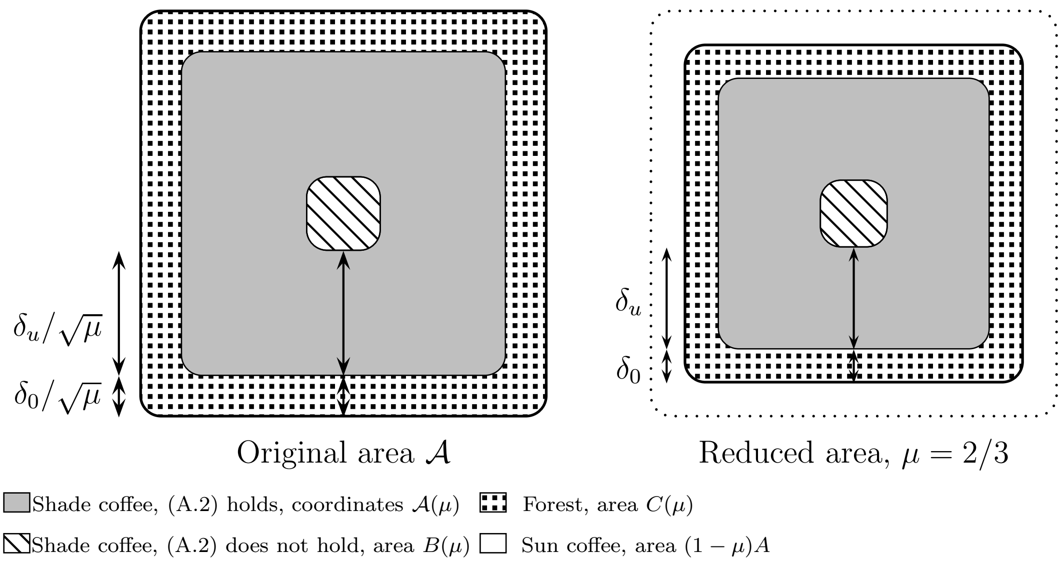

Figure A.1. Illustration of reduction in shade coffee area

A.2 Calibration of the model

In the following we show how the relation (A.1) and the values of $y_{\min}$, α, and β are computed. Klein et al. (2003c) have presented the regression model below for the fruit-set percentage of the *C. canephora* plant:

$$s = a - b\sqrt{d}. \tag{A.4}$$

Here s is the fruit-set percentage of a coffee plant and d is its distance from the pollinator source, i.e., the forest [1]. Klein et al. (2003c) have estimated $a = 94.11$ and $b = 1.15$. Let us assume that the fruit-set percentage, s, and the yield of a coffee plant, $\tilde{y}$, have the relationship $\tilde{y} = \bar{a} + \bar{b}s$. The two unknowns $\bar{a}$ and $\bar{b}$ can be solved for by taking two observations $(\tilde{y}_n, s_n)$ and $(\tilde{y}_f, s_f)$ close to and far from the pollinator source, respectively.

The various yield parameters are collected in Table A.1. According to Ricketts et al. (2004), the average yield for *C. arabica* is $Y_n = 21.5$ fa/ha in an area that is within one kilometer of the pollinator source. One fanega (fa) is 255 kg of fresh coffee or 46 kg of green coffee (Lyngbæk et al., 2001). Beyond one kilometer, the average yield is $Y_f = 17.8$ fa/ha. Assuming that there are 1500 coffee plants in one hectare (Rice and Ward, 1996), we have $\tilde{y}_n = Y_n/1500$ and $\tilde{y}_f = Y_f/1500$. We assume that $\tilde{y}_f$ is the yield at the distance $d_f = 1,000$ m and that d_n is an unknown variable. At the end of this section we explain how d_n is chosen. In the experiments of Ricketts et al. (2004), the pollination services of bees farther than $1,400$ m from the forest were inadequate, and plants farther than 300 m relied 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 (A.4). The values of parameters $\bar{a}$ and $\bar{b}$ are then

$$\bar{a} = (s_f y_n - s_n y_f)/(s_f - s_n) \text{ and } \bar{b} = (\tilde{y}_f - \tilde{y}_n)/(s_f - s_n). \tag{A.5}$$

[1] Although this 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 there being such a relationship being available for *C. arabica*. Olschewski et al. (2006) have considered a regression model similar to (A.4) for forest distance and berry weight. They reason that the ecological mechanisms for coffee pollination services and coffee berry borer infestation are similar in different regions.

Table A.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 (A.1)	—
α	0.1388	Constant in equation (A.1)	—
β	0.002	Multiplier in equation (A.1)	—

The next step is to construct the yield of a plant as a function of distance from the pollinator source. From (A.4) we obtain $\tilde{y}(x) = \min\{\tilde{y}_{\min}, \tilde{\alpha} - \tilde{\beta}\sqrt{d(x)}\}$, where $\tilde{y}_{\min}$ is the minimum yield of a plant (see Table) and

$$\tilde{\alpha} = \bar{a} + \bar{b}a \text{ and } \tilde{\beta} = b\bar{b}. \tag{A.6}$$

Finally, we need to calibrate our model so that function (A.3) produces a realistic yield. The calibration can be done by scaling $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ such that the area of 1065 ha ($A(1) + B(1)$ in (A.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. Recall that $y_{\min}$, α, and β are parameters for infinitesimal pieces of land while $\tilde{y}_{\min}$, $\tilde{\alpha}$, and $\tilde{\beta}$ are the parameters for a plant. In principle, the choice of d_n determines what the final parameters will be. 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 practice, d_n can be found iteratively by solving for the scaling factor ρ and the parameters $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ for a given d_n and then decreasing or increasing it 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 and the corresponding fruit-set percentage $s_n = 66.4\%$.

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 obtained by multiplying $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ by this factor; i.e., the parameters α, β, and $y_{\min}$ used in computations are $\alpha = \rho\tilde{\alpha}$, $\beta = \rho\tilde{\beta}$, and $y_{\min} = \rho\tilde{y}_{\min}$. The calibration parameters are collected in Table A.2.

Table A.2
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 (A.4) 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 (A.6)
$\tilde{\beta}$	3.27×10^{-4}	Distance coefficient in equation determining shade coffee yield as a function of forest distance	Obtained from (A.6)
$\tilde{y}_{\min}$	0.008 $\frac{\text{fa}}{\text{plant}}$	Minimum yield per plant	$Y_{\min}$/(1500 plant/ha)
ρ	0.136 × 46	Scaling factor for $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ to obtain final values	Obtained by requiring the yield of 1,065 ha region to be 20×1,065 fa

A.3 Price and cost parameters

Table A.3
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 4.26 /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

A.4 Sensitivity to prices, protection fee, and minimum wage

The results in the base scenario were computed for a price premium of USD 1.59 /kg, i.e., when the price of shade coffee is 115% higher than that of sun coffee. It is illustrative to compute a minimum price that would guarantee production of shade coffee. When p_1 is kept fixed, the threshold for the price p_2 below which there is no shade coffee production in the equilibrium, is about USD 2.51 /kg, or 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 equilibrium, is about USD 3.01 /kg, The upper and lower thresholds are illustrated as vertical dotted lines in Figure A.2, where the equilibrium and the joint profits maximum are illustrated as a function of p_2. These results suggest that the price premium would have to be quite substantial to attract farmers to maintain shade coffee production. Some studies indicate that certain consumer segments are willing to pay such high premiums, but this is not likely to hold true for all consumers of coffee (Loureiro and Lotade 2005). The actual premiums paid for sustainable coffee have been about USD 1.3 per kg (Giovannucci, 2001).

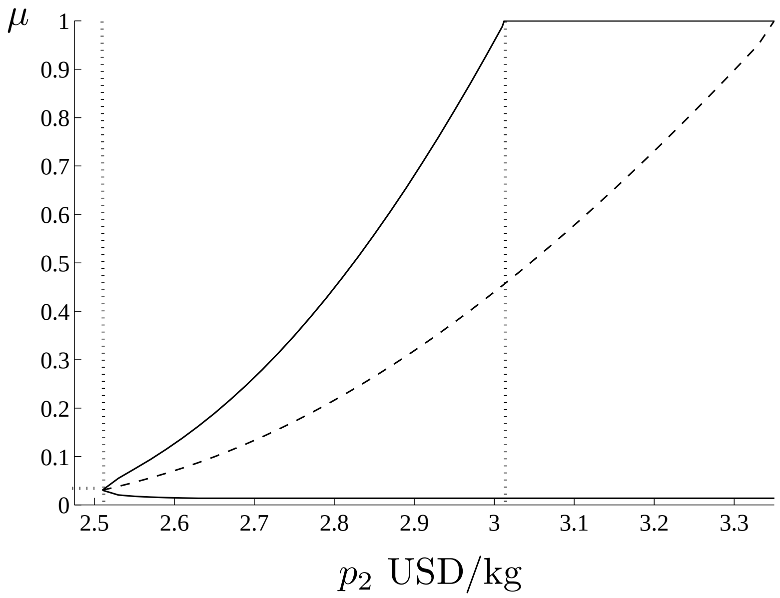

Figure A.2. Illustration of equilibria and joint profits optimum (dashed line) as a function of p_2

It can be expected that introducing a conservation fee (p_3) would increase the area of shade coffee production. 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. As we focus on the choice of technology, the conservation fee is designed to compensate for the preservation of forest area, which is an integral part of sustainable production technology. Such a subsidy would in our model increase forest area by 1.6%, which is a negligible impact compared to the cost; each hectare of forest in addition to the 181 ha in the base scenario equilibrium costs USD 2,700. Naturally, if the forests are valued for benefits other than pollination services, such a payment may be warranted, but our analysis indicates that 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 total equilibrium profits are unaffected by the choice of p_3.

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. [2] Recall from equation (2) in Section 3.1 that the area-dependent costs e_1 and e_2 are divided into labor costs and other costs. 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 allocation of land under equilibrium. Since shade coffee production is more labor intensive, the amount of land allocated to it decreases as the minimum wage increases. An increase of USD 100 (71%) in the minimum wage, i.e., from USD 142 to USD 242, would decrease μ by about 17% in the dominant equilibrium. Due to the similar linear structure of labor costs in both shade and sun coffee production, a substantial increase in the minimum wage would not reduce the shade coffee production area in the same proportion. For an increase of USD 100 in the minimum wage, the conservation fee to compensate for the effect of the higher wage is about USD 277 /ha which is a reasonably high figure. The corresponding increase required for price of shade coffee would be USD 0.06, which is quite low.

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[2] 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.

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