A Bioeconomic Model of Ecosystem Services Provision: Coffee Berry Borer and Shade-Grown Coffee in Colombia.

Shadi S. Atallah
Assistant Professor
Department of Natural Resources and the Environment
University of New Hampshire
Durham, NH
E-mail: shadi.atallah@unh.edu

Miguel I. Gómez
Associate Professor
Charles H. Dyson School of Applied Economics and Management
Cornell University
321 Warren Hall
Ithaca, NY 14853
E-mail: mig7@cornell.edu

Juliana Jaramillo
Scientist, Bayer CropScience
Monheim, 6100 Germany
E-mail: juliana.jaramillo@bayer.com

Selected Paper prepared for presentation at the 18th annual Biodiversity and Economics for Conservation (BIOECON) conference, Cambridge UK, September 14-16, 2016.

A Bioeconomic Model of Ecosystem Services Provision: Coffee Berry Borer and Shade-Grown Coffee in Colombia

Abstract. Transitioning from intensive, sun-grown coffee systems to shade-grown coffee systems is being promoted as a promising ecosystem-based climate adaptation strategy. Intercropping shade trees with coffee trees can produce pest control services, crop growth services through improved soil fertility, and timber. Depending on the shade cover levels, however, the joint production of these services might be complementary or competitive in the way they impact coffee yields. We develop a computational, bioeconomic model to find the range of shade cover for which the benefits of the ecosystem services provided by shade trees justify the ensuing yield reduction associated with shade-grown coffee production systems. First, to model the plant-level provision of pest control services, we specify the relationship between shade, coffee berry temperature, and coffee berry borer infestations. Second, we model shade-induced crop growth ecosystem services through a concave effect of shade cover on coffee yields. Third, we account for the market value of timber in the shade-grown coffee system. We conduct computational experiments to evaluate increasing levels of shade cover and rank them based on farm expected net present values (ENPVs). We do so for three price premium levels for shade-grown coffee. Using parameters from coffee regions in Colombia, and accounting for a moderate price premium for shade-grown coffee ($0.3/kg, or 10%), our simulation results indicate that, under coffee berry borer infestations, the ENPVs in the climate-smart system are higher but only for shade cover levels between 8% and 37%. When a farmer receives a large price premium ($0.5/kg, or 16%), the benefits of shade-induced ecosystem services outweigh the costs and opportunity costs of their provision, even in the absence of coffee berry borer infestations and pest control services.

Keywords: Coffee agroforestry systems, Colombia, computational methods, bioeconomic models, ecosystem services, ecosystem-based adaptation, pest control, production function approach, coffee berry borer.

JEL Codes: C63, Q54, Q57.

Production of coffee, the most valuable tropical export crop worldwide, has been recently affected by increasing temperatures and associated damages due to a variety of pests and diseases (Jaramillo et al. 2011). In particular, the coffee berry borer (CBB), which is the most damaging coffee pest in all coffee-producing countries, has recently been found in higher elevations as a result of rising temperatures across the tropics (Mangina et al. 2010). CBB damage is likely to worsen over time because of a projected increase in both the number of insect generations per year and the number of eggs laid per female borer (Jaramillo et al. 2010). This damage may increase poverty and food insecurity among approximately 120 million people in South America, East Africa, and Southeast Asia (Vega et al. 2003; Jaramillo et al. 2011). Small-scale, asset-poor coffee producers can be disproportionately affected because of their limited financial ability to invest in costly adaptation strategies as well as in more intensive pest and disease management strategies.

Production technologies can be adapted to minimize the uncertainty in coffee production under rising temperatures in tropical areas through the managed provision of ecosystem services. Intercropping shade trees with coffee trees has been promoted as a rational, economically feasible, and relatively easy-to-implement ecosystem-based climate adaptation strategy (Lin 2006; Blackman et al. 2008; Jaramillo 2011; Vignola et al. 2015). First, shade trees can provide pest control services by decreasing the temperature around coffee berries by 4 to 5°C (Beer et al. 1998; Jaramillo 2005). Lowering temperature can keep CBB infestation levels in shaded plantations below a certain threshold compared to infestations in sun-grown plantations (Jaramillo et al. 2013). Second, within an optimal range, shade trees provide yield-increasing crop growth ecosystem services through increased soil fertility and water availability (Beer et al. 1998; Soto-Pinto et al. 2000). Shade trees improve soil fertility by recycling nutrients which are otherwise not accessible to coffee trees and by increasing the soil organic matter from leaf fall, among other mechanisms (Beer 1987). Third, shade-grown coffee systems provide farmers with an additional market-based ecosystem service, namely timber provided by shade trees. For instance, in the American tropics, laurel (*Cordia alliodora* (Ruiz and Pavón) Oken), a fast-growing, valuable timber species, is an additional source of income for coffee farmers (Mussak and Laarman 1989; Somarriba 1992; Somarriba et al. 2001). Finally, shade-grown coffee farmers may receive a price premium for their coffee or direct payments for the ecosystem services they provide (Somarriba 1992; Ferraro, Ushida, and Conrad 2005; Kitti et al. 2009; Barham and Weber 2012). On the other hand, shade-grown coffee systems have lower coffee densities compared to sun-grown systems, and high levels of shade cover can have detrimental impacts on coffee tree yields due to competition for sunlight (Soto-Pinto et al. 2000). Also, shade-grown systems have additional costs related to planting and maintaining shade trees by pruning them.

Disentangling the ecosystem service benefits and costs of sun-grown vs. shade-grown coffee systems requires modeling the joint production of shading-induced ecosystem services. In this paper, we develop a bioeconomic model of multiple ecosystem services provision where services can be complementary or competitive in the way they impact coffee yields. We use established relationships between shade levels, temperature around coffee berries, and coffee berry borer infestations (Jaramillo et al. 2009) to model the provision of pest control under shade-grown coffee systems. Using empirical results on the concave relationship between shade cover and coffee yields (Soto-Pinto et al. 2000), we model the provision of yield-enhancing crop growth ecosystem services while capturing the detrimental effect on yields of high levels of shade cover. Finally, our model accounts for the value of timber and possible price premiums paid by buyers for shade-grown coffee. We simulate increasing shade cover levels to identify ranges for which the economic and ecological benefits provided by shade trees justify the ensuing yield reduction and additional production costs associated with shade-grown production systems.

Modeling Ecosystem Service Provision

Ecosystem production functions are dynamic models that translate the structure and function of ecosystems into the provision of services. In their review of the theory and practice of ecosystem service provision, Daily and Matson (2008) argue that the characterization of these ecosystem production functions is one of the barriers to incorporating ecosystem services into resource decision-making. Barbier (2007) reviews several economic methods for valuing ecosystem services and notes that the production function (PF) approach, compared to survey-based valuation methods, has the advantage of not relying on explanations of hypothetical changes in ecosystem service provision in survey instruments. Instead, it relies on linking the physical effects of changes in the provision of ecosystem services (e.g., pest control) to changes in the prices and quantities of a marketed good (e.g., coffee). In his review of studies that apply the PF approach, Barbier (2007) underscores the promise of integrated ecological-economic modeling of multiple ecological services.

In this paper, we offer a bottom-up version of the PF approach: We use cellular automata and individual-based models to specify the functional relationships at the individual level (i.e., at the tree level). By doing so, the ecosystem production functions are generated from the ecological dynamics (e.g., pest dispersal dynamics) specified at the individual ecological unit level rather than the population or ecosystem level. We characterize the production of multiple ecosystem services that, depending on their level of production, can have competing effects on the yield of the marketed good. Our model incorporates the values of ecosystem services and their cost of production in a bioeconomic farmer decision-making framework. We apply this model to ecosystem-based climate adaptation (Vignola et al., 2015) for the case of a smallholder coffee farmer managing their farm for the simultaneous production of pest control services (coffee berry borer), crop growth services (soil fertility services), and timber production, in addition to the main output, coffee.

Modeling pest control and crop growth services provided by shade trees to neighboring coffee trees requires the modeling of pest dynamics and the impact of shade on yield at the coffee tree level as a function of temperature, time, and space. Pest dispersal is affected by the density and location of individual host and non-host plants (Avelino, ten Hoopen and DeClerck 2011). In the case of shade-grown coffee, the probability of infestation for an individual coffee tree is a function of whether neighboring plants are shade or coffee trees, and whether neighboring coffee trees are infested and at what level. We choose the coffee plant as the modeling unit due to the low mobility of CBB, its host specificity (Avelino, ten Hoopen and DeClerck 2011), the local effect of shade trees on CBB reproduction in neighboring coffee trees (Jaramillo et al. 2009) and per-tree yields (Soto-Pinto et al. 2000).

Among spatially-explicit, dynamic models, cellular automata and individual-based models have become the preferred framework to study socio-ecological complex systems such as diseases and pests in agroecosystems (Grimm and Railsback 2005; Miller and Page, 2007; Atallah et al. 2015).[1] Cellular automata are dynamic models that operate in discrete space and time. Each cell (i.e., a coffee tree) is in one of a finite number of states that get updated according to mathematical functions and algorithms that constitute state transition rules. At each time step t, a cell computes its new state given its old state and that of neighboring cells at $t-1$

[1] See Heckbert, Baynes and Reeson (2010) for a detailed discussion on how individual- or agent-based models relate to cellular automata.

according to certain transition rules (Tesfatsion 2006; Wolfram 1986). These rules can represent bottom-up processes (e.g., pest dispersal) or top-down interventions (e.g., management strategies).

This work assesses the bioeconomics of recommending shade-grown coffee systems as an ecosystem-based adaptation to climate change that ensures the provision of pest control and other ecosystem services while diversifying the sources of income generation for stallholders (Vignola et al., 2015). We contribute to the ecosystem service economics literature by proposing a class of models that can be used to simulate the simultaneous provision of multiple ecosystem services and link the effect of changes in these services to changes in the yield and price of the marketed good. We allow the ecosystem services produced to be either complementary or competitive in the way they affect the main outcome of interest (i.e., coffee yields in our case) (Wossink and Swinton 2007). We formally define the computational bioeconomic model first. Subsequently, we use simulation experiments to calculate farm expected net present values (ENPVs) at various levels of shade cover and shade coffee price premiums. We then identify the range of shade canopy levels for which the ENPVs of shade-grown systems are greater than the ENPVs of sun-grown systems in the presence of a CBB infestation. We find that the ENPV of a system producing the shade-induced ecosystem services is greater than that of a sun-grown system but only for a well-defined range (7.5-37%) of shade, in the presence of coffee berry borer. A sun-grown system generates a higher ENPV, however, if CBB infestations do not occur, unless the price premium is large ($0.5/Kg or 16%).

A Bioeconomic Model of Multiple Ecosystem Services Provision

We develop a model that simultaneously captures the provision of *pest control ecosystem services* (through a shade-induced decreased probability of infestation), changes in the provision of *crop growth ecosystem services* (through the impact of shade trees on coffee yields), and the production of *timber* in a shade-grown coffee system. We use a two-dimensional grid G to represent the spatial geometry of CBB spread in a coffee farm. G is a set of I x J cells where I and J are the numbers of rows and columns, respectively. In a sun-grown system, each cell represents a sun-exposed coffee tree. In a shade-grown system, each cell represents a coffee tree that is either shaded or sun-exposed, depending on the simulated shading levels. In the simulated shade-grown system, farm rows are oriented north to south with I=30 cells per grid row and J=30 cells per grid column, representing a half-hectare coffee plantation with 900 coffee trees (i.e., 1,800 trees/ha). In the simulated sun-grown system, farm rows are oriented north to south with I=55 cells per grid row and J=55 cells per grid column, representing a half-hectare coffee plantation with 3,025 coffee trees (i.e., 6,050 trees/ha).[2]

Each cell (i, j) has a tree type state $\tau_{i,j}$, an infestation state $s_{i,j,t}$, and an age state $a_{i,j,t}$. Tree type state $\tau_{i,j}$ is a 2×1 vector holding a *1* if a cell holds an unshaded coffee tree and a zero if the cell holds a shaded coffee tree. State $s_{i,j,t}$ is the infestation state vector of a coffee tree. Vector $\boldsymbol{P}$, of dimension 4×1, holds a *1* for the state that describes a plant's infection state and zeros for the remaining three states. A coffee tree can be either *Healthy* or *Infested* at a *low* (1-10%), *moderate* (10-25%), or *high* (>25%) level. The three levels of infestation refer to the percentage of berries in each tree that are infested with CBB (Jaramillo et al. 2013). State $a_{i,j,t}$ is

[2] Planting densities used here are equivalent to 1,800 plants /ha and 6,050 plants /ha for shade-grown and sun-grown, respectively. These densities are consistent with those reported in Rice (1996) and Duque and Baker (2003): 1,000-2,000 plants/ha for shade-grown coffee and 4,000 to 7,000 plants/ha for sun-grown coffee.

a *9,125×1* vector holding a *1* for a tree's age in days and a zero for the other ages (the lifetime of a coffee tree is 25 years).

In our model, time t progresses in discrete daily steps up to 9,125 days. A coffee tree's revenue is known to the farmer at time t. The revenue from a cell $r\left(\tau_{i,j}, s_{i,j,t}, a_{i,j,t}\right)$ depends on the type of tree occupying the cell ($\tau_{i,j}$) (determined by shading scenarios), its infestation state ($\boldsymbol{s}_{i,j,t}$) (determined by the stochastic pest dispersal process), and its age ($a_{i,j,t}$) (deterministic variable). In a sun-grown system, coffee yield in each cell is equal to y_{sun}. In a shade-grown system, yield (y_{shade}) initially increases beyond y_{sun} with the shading level ($shade$) due to increased soil fertility and water availability ($\beta_1 > 0$ in Equation 1a). Then, beyond a threshold, additional shade decreases yields due to competition for sunlight ($\beta_2 < 0$ in Equation 1a) (Soto-Pinto et al. 2000). The shading level is defined as the shade canopy cover. We assume that a cell that has a shade tree is entirely covered by shade, and it covers 30% of each of the neighboring cells.[3] Mathematically,

(1a) $$y_{shade} = y_{sun} + \beta_1(shade) + \beta_2(shade)^2, \beta_1 > 0, \ \beta_2 < 0.$$

Shade coffee revenue, $r^{shade}_{s,i,j,t}$, is a function of price ($p_{Healthy,i,j,t}$), yield ($y_{Healthy,i,j,t}$), and pest-related yield reduction ($\tilde{y}_{s_{i,j,t}}$) (equation 1b). Pest-related yield reduction equals 2%, 6%, and 20% when CBB berry infestation is *low* (1-10%), *moderate* (10-25%), and *high* (>25%), respectively (Duque and Baker 2003). Mathematically,

(1b) $$r^{shade}_{s,i,j,t} = p_{Healthy,i,j,t}\ y_{Healthy,i,j,t}\left(1 - \tilde{y}_{s_{i,j,t}}\right).$$

[3] The rate of 30% is tree species-specific. In this model, the rate is obtained through a calibration exercise that seeks to replicate the relationship between shade density (i.e., number of shade trees/ total number of trees) and shade cover in Soto-Pinto et al. (2000).

The timber revenue from a cell occupied by a shade plant is $r_{a,i,j,t}^{timber}$, a function of the age state only (Equation 1c). This parameter equals zero until the shade tree reaches the age of productivity at which point the cell revenue is equal to the product of the timber yield (y_{timber}) and price (p_{timber}).[4] We assume that the farmer harvests timber at *t*=T. Symbols, definitions, values and references for the parameters are presented in Table 1, Table 2, and Table 3.

(1c) $$r_{a,i,j,t}^{timber} \begin{cases} 0 & if\ a_{i,j,t} < \tau_{max} \\ p_{timber}\ y_{timber} & if\ a_{i,j,t} \geq \tau_{max} \end{cases}$$

[Insert Table 1 here]

[Insert Table 2 here]

[Insert Table 3 here]

Given each coffee tree's state $\boldsymbol{s}_{i,j,t}$, and an infestation state transition matrix $\boldsymbol{P}$, its expected infestation state $\mathrm{E}(\boldsymbol{s}_{i,j,t+1})$ at time $t+1$ is computed according to the following infestation-state transition equation:

(2) $$\mathrm{E}(\boldsymbol{s}_{i,j,t+1}) = \boldsymbol{P}^{\mathrm{T}}\ \boldsymbol{s}_{i,j,t}\ ,$$

where E is the expectation operator and $\boldsymbol{P}^{\mathrm{T}}$ is the transpose of matrix $\boldsymbol{P}$. The left-hand side of equation (2) $\mathrm{E}(\boldsymbol{s}_{i,j,t+1})$ is a *4* x *1* vector with a probability of staying in the current infestation state, a probability of transitioning to the next state, and zeroes elsewhere.

We now describe how the infestation state transition probability matrix $\boldsymbol{P}$ governs the plant-level CBB dispersal. Coffee trees in state *Healthy (H)* are susceptible to CBB infestation. CBB attacks a *Healthy* coffee tree with a neighborhood-dependent conditional probability *b*. Infestation starts at the *low* level. The transition from state *Infested-low* to state *Infested-moderate* happens with a conditional probability d. Similarly, a transition from state *Infested-*

---

[4] Here we only consider the value of timber. The laurel tree is also grown for fruits, honey production, and ethanol production, among other uses (Liegel and Stead 1990).

moderate to state *Infested-high* happens with a conditional probability f. Mathematically, ***P*** can be expressed as follows:[5]

$$(3) \qquad \boldsymbol{P} = \begin{pmatrix} 1-\ b & b & 0 & 0 \\ 0 & (1-d) & d & 0 \\ 0 & 0 & (1-f) & f \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

In equation (3), b is the *Healthy* to *Infested-low* transition probability conditional on previous own and neighborhood infestation states; and on current own, and neighborhood tree type states. It can be expressed as

$$(4) \qquad b = \Pr\left(s_{i,j,t+1} = I_{low} \,\middle|\, s_{i,j,t} \ = \ H\right)$$

$$= \qquad 1 - e^{-\alpha(T)} \begin{cases} 0 \ \text{ if } N_{i,j,t} \ has\ no\ infested\ coffee\ plants\ ) \\ \text{if } N_{i,j,t} = \ has\ at\ least\ one\ infested\ coffee\ plant) \end{cases}$$

In equation (4), $N_{i,j,t}$ indicates whether there are any infested coffee trees among the eight neighbors of a coffee tree (figure 1). This type of neighborhood, called Moore neighborhood, is consistent with observed patterns of CBB dispersal where the pest is shown to spread from tree to tree without any directional preference (Ruiz-Cárdenas et al. 2009). Consider a healthy coffee tree that is surrounded by healthy coffee trees with or without shade trees. The probability that it will get infested in the next time step equals zero. If it has at least one infested neighbor, a tree-to-tree infestation occurs with temperature-dependent rate parameter $\alpha(Temp)$ that increases with temperature according to $\alpha(T) = -0.005689 + 0.00381\ Temp$, where $Temp$ is the net temperature (in Celsius degrees) around the berries (Jaramillo et al. 2009). The net temperature is defined here as the difference between the ambient temperature and the reduction in temperature provided by a shade tree. The time a coffee tree with at least one *Infested* neighbor stays in the *Healthy* state before transitioning to the *Infested-low* state is an exponentially distributed random

[5] ***P*** reads from row (states H, I_L, I_M, and I_H at time t) to column (states H, I_L, I_M, and I_H at time $t+1$).

variable, with rate $\alpha\ (T)$. In each time step (i.e., on any day during the production season), a random variable u_t determines whether or not a coffee tree transitions from the *Healthy* state to the *Infested-low* state. A *Healthy* coffee tree that has one *Infested* neighbor and no mature shade trees around it is infested by the pest at time *t+1* if $u_t < 1 - e^{-\alpha(T)}$, where u_t is a random draw from $U\sim$ (0, 1). Conversely, the pest does not colonize the neighboring tree if $u_t \geq 1 - e^{-\alpha(T)}$. Changes in probability *b* due to shade trees allow for an explicit modeling of the first channel through which pest control services are produced in a shade-grown coffee system.

[Insert figure 1 here]

The probability of transitioning from *Infested-low (I_L) to Infested-medium (I_M)* is given by the conditional probability d as follows:

(5) $$d = \Pr\left(s_{i,j,t+1} = I_M \,\middle|\, s_{i,j,t} = I_L\right) = \begin{cases} 1 - e^{-1/L_1} & \text{if } N_{c,i,j,t} \text{ has no shade plant} \\ 0 & \text{otherwise} \end{cases}$$

This probability depends on a coffee tree's neighborhood state as well. Coffee trees that have a mature shade tree in their neighborhood never reach the *Infested-medium* state (Jaramillo et al. 2013). Those that do not have a mature shade plant in their neighborhood spend a period L_1 in state *Infested-low* (I_L) before they transition to state *Infested-moderate* (I_M). The waiting time after a coffee tree enters state I_L and before it transitions to state I_M is a random variable, exponentially distributed with fixed rate parameter $1/L_1$.

The *Infested-medium (I_M)* to *Infested-high (I_H)* state transition probability is given by conditional probability f as follows:

(6) $$f = \Pr\left(s_{i,j,t+1} = I_H \,\middle|\, s_{i,j,t} = I_M\right) = \begin{cases} 1 - e^{-1/L_2} & \text{if } N_{c,i,j,t} \text{ has no shade plant} \\ 0 & \text{otherwise} \end{cases}$$

Similarly to Eq. (5), this probability depends on a coffee tree's neighborhood state. Coffee trees that have a mature shade plant in their neighborhood never reach the heavily infested state (Jaramillo et al. 2013). For coffee trees that do not have a mature shade tree in their neighborhood, the waiting time after they enter state *Infested-moderate* (I_M) and before they transition to state *Infested-high* (I_H) is a random variable, exponentially distributed with fixed rate parameter $1/L_2$. Symbols, definitions, values and references for the model parameters are presented in Table 2. Changes in probabilities *d* and *f* due to the presence of shade trees allow us to model a second channel of pest control service provision. While the first channel (changes in probability *b*) reduces the initial infestation probability, the second channel (changes in probabilities *d* and *f*) keeps the infestations at low levels (Jaramillo et al. 2009).

The objective of a risk-neutral coffee farmer is to maximize the farm's ENPV by choosing an optimal shading strategy from a set of strategies $\mathcal{W}$. Each strategy consists of a percentage canopy cover and translates into a binary decision for each cell (i, j) at the beginning of each simulation whereby $u_{i,j,0} = 1$ if a coffee tree is removed and replaced with a shade plant and 0 otherwise for each (i, j) at $t = 0$. Once a coffee tree has been replaced, it takes the shade tree τ_{max} periods to reach maturity at which point it has an economic value and provides shade-induced ecosystem services to its neighboring coffee trees, thus reducing conditional probabilities b, d, and f and affecting crop yield.

The optimal strategy $\mathcal{W}^*$ is the set of cell-level control variables $\{u_{i,j,0}\}$ that allocates effort (i.e., planting and maintaining shade trees) over space so as to yield the maximum ENPV over the time horizon. Letting E be the expectation operator over the random cell-level revenues $r\left(\boldsymbol{\tau}_{i,j}, \boldsymbol{s}_{i,j,t}, \boldsymbol{a}_{i,j,t}\right)$ and ρ^t the discount factor [6] at time *t* (in days) where $t \in \{0, 1, 2, \ldots, 9125\}$, the objective of a coffee farmer is to maximize the ENPV as follows:

[6] $\rho^t = \frac{1}{(1+r)^t}$, where r is the discount rate.

$$(7)\ \max_{\mathcal{W}} \mathrm{E} \sum_t^T \rho^t \sum_{(i,j)}^G \left\{ \begin{array}{c} \left(1 - \sum_{\tau=0}^{\tau_{max}} u_{i,j,0}\right) \left[r\left(\boldsymbol{\tau}_{i,j}, \boldsymbol{s}_{i,j,t},\ \boldsymbol{a}_{i,j,t}\right) - c_{i,j,t} \right] \\ -u_{i,j,0}\ (c_{u_{i,j,0}} + c_{u_{i,j,t}}) \end{array} \right\}$$

subject to equation (2) $\mathrm{E}(\boldsymbol{s}_{i,j,t+1}) = \boldsymbol{P}^{\mathrm{T}}\ \boldsymbol{s}_{i,j,t}$.

The expression in the square brackets of equation (7) represents the revenue generated by a plant in location(i,j), which depends on its tree type ($\boldsymbol{\tau}_{i,j}$), infestation ($\boldsymbol{s}_{i,j,t}$) and age ($\boldsymbol{a}_{i,j,t}$) states at time *t*. If the farmer decides to plant a shade tree in cell (i,j) at *t* = 0, then $u_{i,j,0}$ is equal to 1 and the revenue from that cell is equal to zero for τ_{max} periods thus capturing the waiting time until shade trees start providing ecosystem services. If the farmer has left the coffee tree in cell (i,j) *t* = 0, then $u_{i,j,0}$ is equal to 0 and the revenue from that cell is equal to $r_c(\boldsymbol{s}_{i,j,t})$ minus the unit cost of coffee production $c_{i,j,t}$. Binary variable $u_{i,j,0}$ pre-multiplies two unit costs associated with shade trees. The first unit cost, $c_{u_{i,j,0}}$, is the cost of planting the shade tree and the second unit cost, $c_{u_{i,j,t}}$, is the unit cost of maintaining of shade trees through fertilization and pruning.

Model Initialization

Coffee trees are initialized at planting and assumed not to bear fruit until year 4 (Equation 1c). The beginning of each simulation run represents the start of a calendar year. Coffee trees are initialized as *Healthy*. In September, when berries are ripe, a small percentage (0.5%) of the coffee trees are randomly chosen from a uniform spatial distribution U (0, $I * J$) to transition from *Healthy* to *Infested-low*. This initialization reflects findings in CBB studies indicating that infested coffee berries from the previous growing season act as a source of re-infestation in the following season (Jaramillo et. al 2006). Subsequently, CBB spreads to *Healthy* coffee trees according to the state transition described in equation (1) until harvest, which occurs in December. At harvest, CBB populations drop dramatically but infested berries left after harvest, either on the ground or on the tree, act as a source of season-to-season re-infestation. Infested coffee trees stay in state *Infested-low* until the berries of the next growing season have reached maturity in the following September, and pest dispersal resumes (Jaramillo et. al 2006).

Model calibration and parameterization

We calibrate Eq. (1a) by findings the values of β_1 and β_2 that generate the concave relationship between shade cover and coffee yields per plant reported in Soto-Pinto et al. (2000). For all other parameters, we choose values from ranges reported in the literature and by consulting scientist experts on CBB (Table 2). We choose a daily time step to be consistent with the time units of CBB dispersal parameters (Railsback and Johnson 2011). Sun-grown and shade-grown production parameters are presented in Table 3.

Experimental Design

We design and implement experiments to produce ENPV observations for increasing shading levels. We evaluate the discrete set of shading strategies by comparing their ENPVs to those resulting from a strategy of no-shade (i.e., a sun-grown production system). Each experiment consists of a set of 100 simulation runs, over 9,125 days (25 years), on a coffee farm of 900 coffee trees for the shade-grown coffee experiments and 3,025 coffee trees for the sun-grown coffee experiments. We define shade levels as the percentage of shaded cells over the total number of cells on the grid.

Survey data indicate that, in most cases, shade trees are recruited from the naturally occurring regeneration (Somarriba 1992 and references therein). We, therefore, assign the location of shade trees using random draws from a uniform distribution. We add a condition to the model that prevents selecting two contiguous cells to hold shade trees. We relax this condition at higher shading levels where it becomes impossible to add shade trees without having two contiguous cells occupied by shade trees. Outcome realizations for a run within an experiment differ due to random spatial initialization of the CBB infestation and the shading strategies and due to subsequent random spatial pest dispersal. Data collected over simulation runs are the expected net present values (ENPV). To find the ENPV-maximizing shading strategy, we employ the objective function (equation 7) to rank the coffee farm ENPV under the alternative strategies. The model is written in Java and simulated using the software AnyLogic™ (XJ Technologies).

Results

We first present the results the ENPVs of a sun-grown coffee farm and those of a shade-grown farm with increasing levels of shade cover. We then discuss how the ENPVs of shade-grown systems change when a farmer receives a large shade-grown coffee price premium vs. no premium at all.

The economics of shade-induced ecosystem services with and without CBB infestation

Our simulation results for the shade-grown system indicate that there is a shade range (1-20%) for which pest control services, crop growth services, and timber are complementary in the way they impact yields and consequently ENPVs. However, beyond 20% shade cover, while additional shade is still beneficial for the provision of pest control services and timber, it reduces ENPVs through its detrimental effect on coffee tree yields (according to Eq. 1a). Soto-Pinto et al. (2000) indicate the negative effect of shade cover on coffee yields beyond a certain threshold is due to the coffee trees' sensitivity to sunlight (solid line, Figure 2). When ecosystem services are jointly produced, increasing shade levels to augment the provision of one ecosystem service (i.e., pest control) without considering the tradeoffs implied on other ecosystem services (i.e., crop growth) may be economically detrimental to the whole system.

In the presence of CBB infestations, there are shade ranges (7-37%), for which pest control services, crop growth services, and timber cause the ENPV of a shade-grown system to be greater than that of a sun-grown system (Figure 2b). In our model, the higher ENPV under a shade-grown system is driven by its resilience to CBB infestations, i.e. pest control services, rather than crop growth services and timber production. In fact, when we simulate the systems without CBB infestations, the sun-grown coffee farm generates higher ENPVs than the shade-grown coffee farm. The maximum value of crop growth ecosystem services and timber provided by shade cover is not enough to offset the forgone coffee yields and greater production costs in a shade-grown system compared to a sun-grown system (Figure 2a). The maximum difference in ENPVs between a shade-grown and a sun-grown system in the presence of CBB infestations is $13,000/0.5 ha or $26,000/ha over 25 years and represents a difference of 77% over the ENPV of a sun-grown system. This maximum difference occurs at the 20% shade cover level (Fig. 2).

[Insert Figure 2 here]

The role of price premiums in production system decisions

To understand the relationship between the price premium and the relative cost-effectiveness of shade-grown coffee with respect to sun-grown coffee, we reproduce results in Figure 2 for two alternative price premium cases. While the baseline case has a net price premium of $0.25/kg or 8%, we consider here a case where the farmer receives no price premium and a case where the net price premium is $0.5/kg or 16%. These additional cases are important to recognize that authors have estimated price premiums paid to shade-grown coffee farmers that are lower and higher than our baseline value. These premiums are 40% and 2% in Colombia in 2002 and 2013, respectively (Rueda and Lambin 2013), 7% in Peru (Barham and Weber 2012) and 20% in Ethiopia (Takahashi and Todo 2013).[7] Shade coffee certification programs seek to link environmental and economic goals through a price premium, as payment for the ecosystem services provided by shade. This premium might or might not be enough to compensate a farmer for the low yields that ensue from the shade levels required under these programs (Perfecto et al. 2005).

As expected, our results suggest that, in the absence of CBB infestations, if a farmer receives no price premium, the ENPV of a shade-grown system is always lower than that of a sun-grown system no matter the shade level (Fig. 3a). Similarly to the baseline case, in the presence of CBB infestations, we find a range for which a shade-grown system generates a higher ENPV than a sun-grown system (Fig. 3b). However, when there is no price premium for shade-grown coffee, the range for which the ENPV of the shade-grown system is greater than that of the sun-grown system is narrower: 10-32% when there is no premium (Fig. 3b), compared to 7-37% in the baseline case (Fig. 2b). Overall, these results indicate that, in addition to increasing farm ENPV, the price premium widens the range of shade cover that a farmer can afford to augment the provision of ecosystem services on the farm. Larger ranges, in turn, mean that farmers can comply with stricter shade-grown certification requirements in an economically sustainable way.

[Insert Figure 3 here]

When a farmer receives a net price premium of $0.5/kg or 16%, we find a shade cover range where a shade-grown system produces higher ENPVs than those of a sun-grown system, regardless of whether or not a farm is infested by CBB. In this case, the benefits of shade-

[7] The corresponding net premiums would be 1% and 20% for Colombia), 3.5% for Peru, and 10% for Ethiopia, assuming that certification costs can amount to half of the premiums (Gómez et al. 2011).

induced ecosystem services outweigh the costs and opportunity costs of their provision, even if pest control services are excluded. This result illustrates how high the net price premium needs to be for a shade-grown system to yield higher ENPVs than a sun-grown system if the decision to recommend or adopt a shade-grown system is made irrespective of the likelihood of CBB infestations. In the presence of CBB infestations, the shade cover range for which the ENPVs of a shade-grown system are higher than those of a sun-grown system is 6-40% (Fig. 4b), compared to 7-37% in the baseline case. At this price premium, the ENPV-maximizing shade cover is 25% (Fig. 4), higher than when the price premium is lower or nonexistent (20%; Fig. 2 and Fig. 3).

[Insert Figure 4 here]

Conclusions

Broadly, our results are consistent with previous empirical findings suggesting that, unless certified coffee premiums are large, the best management practices required by certifiers (e.g., shade-grown system) might increase profitability for coffee farmers through yields rather than price premiums (Valkila 2009; Barham and Weber 2011). Certification agencies require a minimum shade cover as a condition for the farmer to receive a price premium. These minimum requirements are not based on a bioeconomic, dynamic accounting for multiple ecosystem services. By characterizing the ecosystem production functions in this model and recognizing complementarity and competition among the ecosystem services produced, we are able to identify the range of shade cover that will not leave a farmer worse off under a shade-grown system, compared to a sun-grown system. For instance, the Smithsonian Migratory Bird Center's shade-grown certification requires a minimum of 40% shade cover (Coffee and Conservation 2016). Under the parameter values in this model, this requirement might leave a farmer with lower ENPVs under a shade-grown system than under a sun-grown system, unless they receive a large shade-grown price premium that is far greater than reported values (16% vs. 2% in Rueda and Lambin 2013).

Future model extensions can incorporate the risk of coffee rust infestations: Shading levels that are beneficial for controlling the CBB might be detrimental for controlling coffee rust infestations, especially in coffee ecoregions with high precipitation and humidity levels. In these regions, we expect the optimal shade levels to be lower than the levels indicated in this article. On the other hand, we omitted here other ecosystem services that might cause the optimal shading levels to be greater; these include pollination services (Ricketts and Lonsdorf 2013) and shade-induced coffee sensory attributes (Läderach et al. 2011).

Besides providing a framework to simulate and assess the cost-effectiveness of augmenting ecosystem service provision, this model is an example of how researchers can integrate bioeconomic decision-making tools with ecosystem functions for which there is sufficient scientific knowledge. In our case, we built on already-established relationships between environmental factors such as temperature, ecological dynamics such as pest dispersal and agro-ecological outcomes such as coffee yields under shade to model the provision of pest control services, crop growth services, and timber. Our approach can be viewed as a bottom-up equivalent to Barbier (2007)'s PF approach.

The model, with sub-models for each ecosystem service, can be used for other applications where recommended transitions in agricultural or natural resource management systems induce changes in ecosystem services characterized by complex complementary and competitive relationships. For instance, it can be applied to systems such as cocoa and tea plantations where shade cover is recommended for climate resiliency and product differentiation as in the case of coffee. For applications where ecosystem services are produced through different agro-ecological processes, the sub-models used here would need to be modified, but the bioeconomic framework used to study the bioeconomics of the ecosystem-based adaptation remains.

References

Atallah, S. S., M. I. Gómez, J. M. Conrad and J. P. Nyrop. 2015. A Plant-level, Spatial, Bioeconomic Model of Plant Disease Diffusion and Control: Grapevine Leafroll Disease. *American Journal of Agricultural Economics* 97 (1): 199-218

Avelino, J., ten Hoopen, G. M., and DeClerck, F. 2011. Ecological mechanisms for pest and disease control in coffee and cacao agroecosystems of the neotropics. In *Ecosystem Services from Agriculture and Agroforestry*, ed. Rapidel et al., 91-118. London: Earthscan.

Barbier, E. B. (2007). Valuing ecosystem services as productive inputs. *Economic Policy*, *22*(49), 178-229.

Barham, B. L., and Weber, J. G. 2012. The economic sustainability of certified coffee: Recent evidence from Mexico and Peru. *World Development*, 40 (6), 1269-1279.

Beer, J., Muschler, R., Kass, D., and E. Somarriba. 1998. Shade management in coffee and cacao plantations. *Agroforestry Systems* 38: 139–164

Blackman, A., Albers, H. J., Avalos-Sartorio, B., and Murphy, L. C. 2008. Land cover in managed forest ecosystem: Mexican shade coffee. *American Journal of Agricultural Economics*, 90(1), 216–231

Chamorro G., Gallo A. and Lopez R. 1994. Evaluación económica del sistema agroforestal café asociado con nogal. *Cenicafé* 45(4): 164–170

Coffee and Conservation 2016. Quick guide to coffee certifications. Available at http://www.coffeehabitat.com/certification-guide/. Last accessed 8/31/2016

Daily, G. C., & Matson, P. A. 2008. Ecosystem services: From theory to implementation. *Proceedings of the national academy of sciences*, *105*(28), 9455-9456.

Ferraro, P. J., Uchida, T., and Conrad, J. M. 2005. Price premiums for eco-friendly commodities: are ‘green’markets the best way to protect endangered ecosystems? *Environmental and Resource Economics*, 32(3), 419-438.

Gómez, M.I., Barrett, C.B., Buck, L.E., De Groote, H., Ferris, S., Gao, H.O., McCullough, E., Miller, D.D., Outhred, H., Pell, A.N. and Reardon, T., 2011. Research principles for developing country food value chains. *Science*,*332*(6034), pp.1154-1155.

Grimm, V., and Railsback, S. F. 2005. *Individual-based modeling and ecology*. Princeton university press.

Heckbert, S., Baynes, T., and Reeson, A. 2010. Agent-based modeling in ecological economics. *Annals of the New York Academy of Sciences*, *1185*(1), 39-53.

Jaramillo A. 2005. Andean climate and coffee in Colombia. Colombian National Federation of Coffee Growers. Centro Nacional de Investigaciones de Cafe´– Cenicafe´. Chinchina, Colombia. 192p. (in Spanish).

Jaramillo, J., C. Borgemeister, and P. Baker. 2006. “Coffee berry borer *Hypothenemus hampei* (Coleoptera: Curculionidae): searching for sustainable control strategies.” *Bulletin of Entomological Research* 96 (3): 223-233.

Jaramillo J, Chabi-Olaye A, Kamonjo C, Jaramillo A, Vega FE, et al. 2009. Thermal Tolerance of the Coffee Berry Borer *Hypothenemus hampei*: Predictions of Climate Change Impact on a Tropical Insect Pest. *PLoS ONE* 4(8).

Jaramillo, J., Chabi-Olaye, A., and Borgemeister, C. 2010. Temperature-dependent development and emergence pattern of *Hypothenemus hampei* (Coleoptera: Curculionidae: Scolytinae) from coffee berries” *Journal of Economic Entomology*, *103*(4), 1159-1165.

Jaramillo, J., Muchugu, E., Vega, F. E., Davis, A., Borgemeister, C., and Chabi-Olaye, A. 2011. Some like it hot: the influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. *PLoS One*, 6(9), e24528.

Jaramillo, J., Setamou, M., Muchugu, E., Chabi-Olaye, A., Jaramillo, A., Mukabana, J.,and Borgemeister, C. 2013. Climate Change or Urbanization? Impacts on a Traditional Coffee Production System in East Africa over the Last 80 Years. *PloS one*, *8*(1), e51815.

Johnson, M. D., Kellermann, J. L., and Stercho, A. M. 2010. Pest reduction services by birds in shade and sun coffee in Jamaica. *Animal conservation*, 13(2), 140-147.

Kitti, M., Heikkila, J., and Huhtala, A. 2009. 'Fair' policies for the coffee trade—Protecting people or biodiversity? *Environment and Development Economics*, 14(6), 739–758

Läderach, P., Oberthür, T., Cook, S., Iza, M. E., Pohlan, J. A., Fisher, M., & Lechuga, R. R. (2011). Systematic agronomic farm management for improved coffee quality. *Field Crops Research*, *120*(3), 321-329.

Liegel, L.H., and J.W. Stead. 1990. Cordia alliodora (Ruiz and Pav.) Oken: laurel, capá prieto. *In* R.M. Burns and B.H. Honkala (Techn. Coords.). Silvics of North America, volume 2, Agricultural Handbook 654, pp. 270-277. U.S. Department of Agriculture, Washington, D.C. Available at http://www.na.fs.fed.us/pubs/silvics_manual/volume_2/cordia/alliodora.htm. Last accessed 7/14/2014.

Lin, B. B. 2007. "Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture." *Agricultural and Forest Meteorology*, *144*(1), 85-94.

Mangina FL, Makundi RH, Maerere AP, Maro GP, and Teri JM. 2010. “Temporal variations in the abundance of three important insect pests of coffee in Kilimanjaro region, Tanzania.” In: 23rd International Conference on Coffee Science. Bali, Indonesia 3–8 October 2010. ASIC, Paris

Miller, J. H. and S. E. Page, .2007. “Complex Adaptive Systems: An Introduction to Computational Models of Social Life.” Princeton University Press, Princeton, USA, 284 pp.

Mussak, M. F., and Laarman, J. G. 1989. Farmers' production of timber trees in the cacao-coffee region of coastal Ecuador. *Agroforestry systems*, 9 (2), 155-170.

Perfecto, I., Vandermeer, J., Mas, A., and Pinto, L. S. 2005. Biodiversity, yield, and shade coffee certification. *Ecological Economics*, *54*(4), 435-446.

Ricketts, T.H. and Lonsdorf, E. (2013). Mapping the margin: comparing marginal values of tropical forest remnants for pollination services. *Ecological Applications*, *23*(5), pp.1113-1123.

Rueda, X., and E. F. Lambin (2013). Responding to globalization: impacts of certification on Colombian small-scale coffee growers. *Ecology and Society* 18 (3): 21.

Ruiz-Cárdenas, R., Assunção, R. M., & Demétrio, C. G. B. (2009). Spatio-temporal modelling of coffee berry borer infestation patterns accounting for inflation of zeroes and missing values. *Scientia Agricola*, *66*(1), 100-109.

Somarriba, E. 1992. “Timber harvest, damage to crop plants and yield reduction in two Costa Rican coffee plantations with *Cordia alliodora* shade trees.” *Agroforestry systems* 18, no. 1: 69-82.

Soto-Pinto, L., Perfecto, I., Castillo-Hernandez, J., & Caballero-Nieto, J. (2000). Shade effect on coffee production at the northern Tzeltal zone of the state of Chiapas, Mexico. *Agriculture, Ecosystems & Environment*, *80*(1), 61-69.

1_2%20Sustainable%20Agriculture%20Standard_docx(1).pdf. Last accessed 7/24/2014

Takahashi, R., & Todo, Y. (2013). The impact of a shade coffee certification program on forest conservation: a case study from a wild coffee forest in Ethiopia. *Journal of Environmental Management*, *130*, 48-54.

Teodoro A, Klein AM, Reis PR, and Tscharntke T. 2009. "Agroforestry management affects coffee pests contingent on season and developmental stage." *Agricultural and Forest Entomology* 11: 295–300.

Tesfatsion, L., and K. L. Judd (ed.). 2006. Handbook of Computational Economics, Elsevier, edition 1, volume 2, number 2.

United States Department of Agriculture Foreign Agricultural Service 2014. "Colombia Coffee Annual Subsidies Subside as Prices Climb and Production Recovers", GAIN report, available at http://gain.fas.usda.gov/, last accessed 7/21/2014.

Valkila, J., 2009. Fair Trade organic coffee production in Nicaragua—Sustainable development or a poverty trap? *Ecological Economics*, *68* (12), pp.3018-3025.

Vega, F.E., Rosenquist, E., and Collins, W. 2003. "Global project needed to tackle coffee crisis." *Nature* 425 (6956), 343.

Wolfram, S. (ed.). 1986. "Theory and Applications of Cellular Automata." World Scientific, Singapore.

Table 1. Coffee tree yield and quality reduction parameters

Infestation state ($s_{i,j,t}$)	Berry infestation level (%)	Yield reduction (%)[a]
Healthy, $s_{i,j,t} = H$	<1	0
Infested Low, $s_{i,j,t} = I_L$	1-10	2
Infested Moderate, $s_{i,j,t} = I_M$	10-25	6
Infested High, $s_{i,j,t} = I_H$	>25	20

[a] Duque and Baker (2003)

Table 2. CBB dispersal parameters

Parameter	Description	Value	Unit	Sources
α	Temperature-dependent exponential probability rate parameter	$\alpha(Temp) = a + b\,Temp$	day^{-1}	Jaramillo et al. 2009
a	intercept	-0.006	n/a	Jaramillo et al. 2009
$Temp$	Temperature	21-24	°C	Jaramillo et al. 2009
b	slope	0.003	n/a	Jaramillo et al. 2009
L_1	Average waiting time between I_L and I_M state, no shade.	15	days	Johnson et al. (2009).
L_2	Average waiting time between I_M and I_L state, no shade.	120	days	Johnson et al. (2009) and Ruiz-Cardenas et al. (2009).

Table 3. Sun-grown and shade-grown coffee production parameters

Parameter	Description	Unit	Coffee production system: Sun	Shade
			Value[a]	
Coffee				
$y_{sun(s_{i,j,t}=Healthy)}$	Yield-sun [a]	Kg/tree/year[b]	0.82	n/a
$y_{shade(s_{i,j,t}=Healthy)}$	Yield-shade [g]	Kg/tree/year[b]	n/a	Eq. 1a
β_1	Yield-shade		n/a	0.0175
β_2	parameters		n/a	-0.0002
$p_{(s_{i,j,t}=Healthy)}$	Price[c]	USD/kg	3.16	3.16; 3.41; 3.66
$c_{i,j,t}$	Production cost[d]	USD/tree/year[b]	1.28	1.28
$c_{u_{i,j,0}}$	Coffee removal cost[d,e]	USD/tree	n/a	0.12
Timber				
y_{shade}	Yield	inches/tree/year[b]	n/a	0.0099295
p_{shade}	Price[d]	USD/inch	n/a	537
$c_{u_{i,j,0}}$	Planting cost	USD/ tree	n/a	0.12
$c_{u_{i,j,t}}$	Maintenance cost[d]	USD/ tree	n/a	0.09
ρ	Discount factor [f]	year $^{-1}$	10%	10%

n/a is not applicable

[a] Parameter values are from Chamorro, Gallo and López (1994), unless otherwise noted.

[b] Note that these values are expressed in per-day terms in the model.

[c] National Coffee Federation in Colombia, Price list, May 13 2013

[d] Values are expressed in real terms.

[e] Duque and Baker (2003).

[f] Value equivalent to an annual discount rate of 10%.

[g] Soto-Pinto et al. (2000)

Table 4. Sun-grown vs Shade-grown coffee: effect on expected net present values (ENPV); $p_{shade} = \$3.41/kg$; $p_{sun} = \$3.16/kg$

	No CBB		CBB	
Coffee system	*ENPV* [b] ($/ha)	*Percent change in ENPV* [a]	*ENPV* ($/ha)	*Percent change in ENPV* [a]
Sun-grown	33,462	n/a	16,974	n/a
Shade-grown (% canopy cover)				
5	20,001	-40%	12,779	-25%
7.5	23,264	-30%	17,814	5%
10	25,977	-22%	22,819	34%
15	28,653	-14%	27,081	60%
20	30,381	-9%	30,027	77%
25	29,580	-12%	29,202	72%
30	27,146	-19%	26,925	59%
35	21,043	-37%	20,838	23%

n/a is not applicable

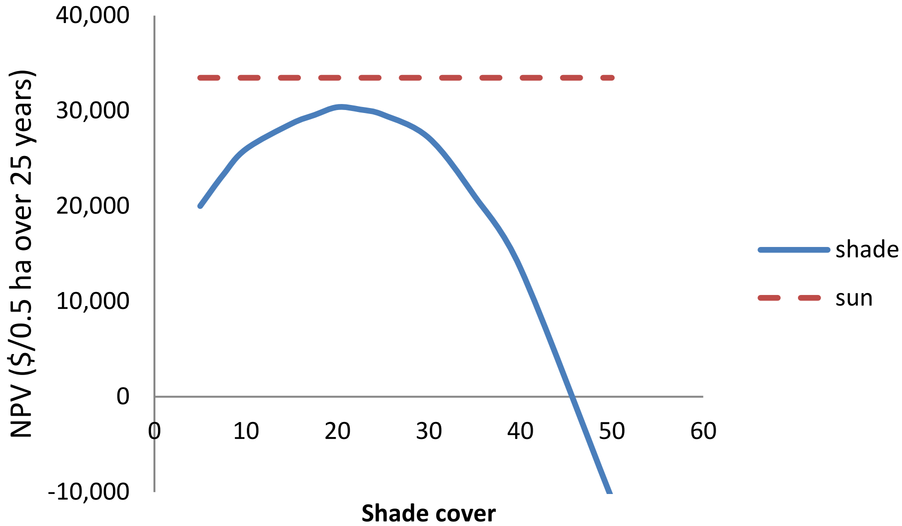
[a] Percent change in ENPV=[ENPV (Shading strategy)-ENPV (Sun-grown)]/ ENPV (Sun-grown)

[b] Expectations are obtained from 100 simulations

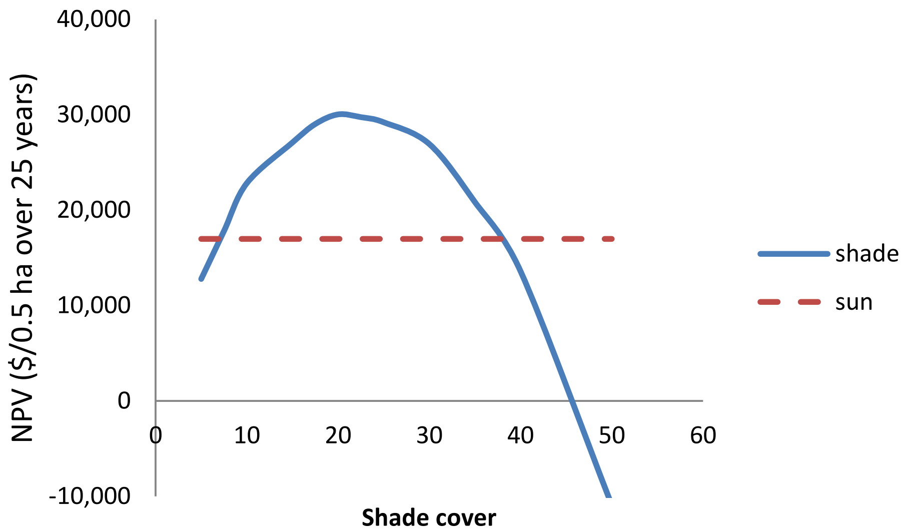
Figure 1. Neighborhood of a coffee plant (*i, j*)

i-1, j-1	*i-1,j*	*i+1,j +1*
i,j-1	*i, j*	*i, j+1*
i+1, j-1	*i+1, j*	*i+1, j+1*

Figure 2. Effect of shading on coffee farm expected net present values (ENPV) in a sun-grown and a shade-grown coffee system (data points are from Table 4; $p_{shade} = \$3.41/kg$).

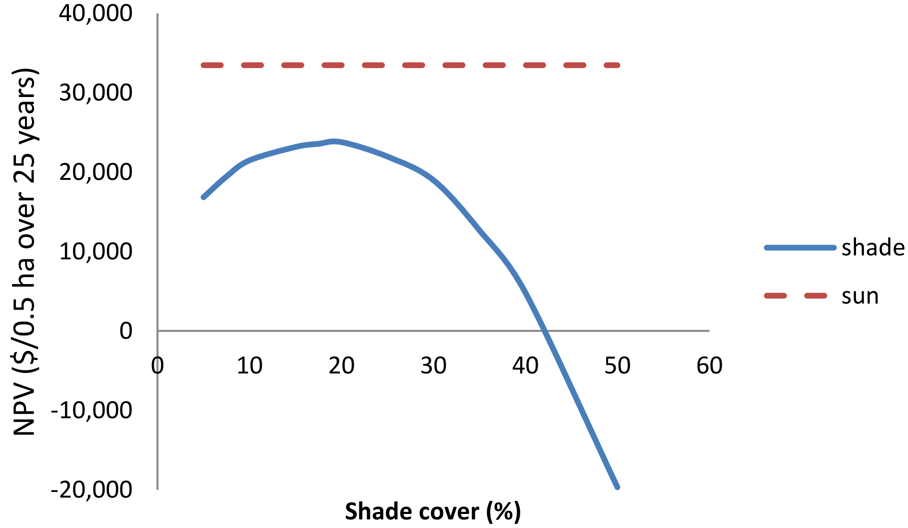


a. No CBB infestation

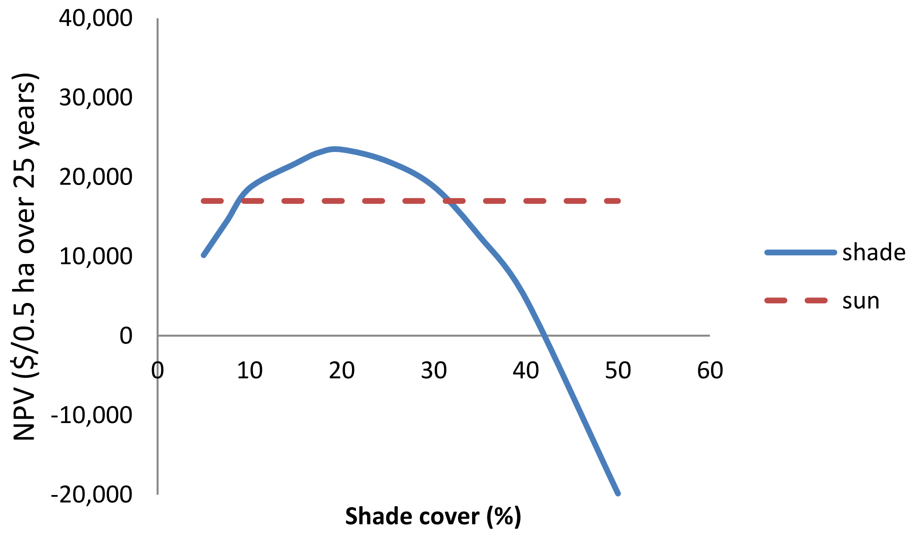


b. CBB infestation

Figure 3. Effect of shading on coffee farm expected net present values (ENPV) in a sun-grown and a shade-grown coffee system (data points are from Table 5; $p_{shade} = p_{sun} = \$3.16/kg$).

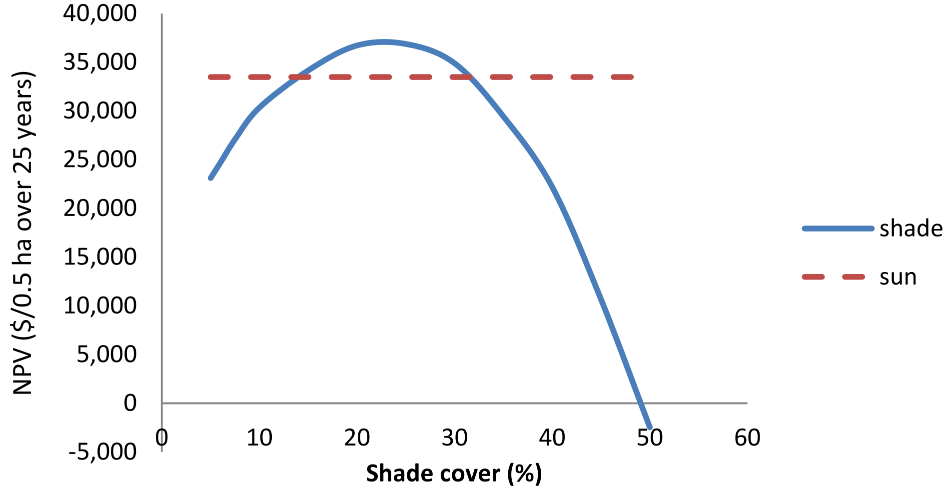


a. No CBB infestation

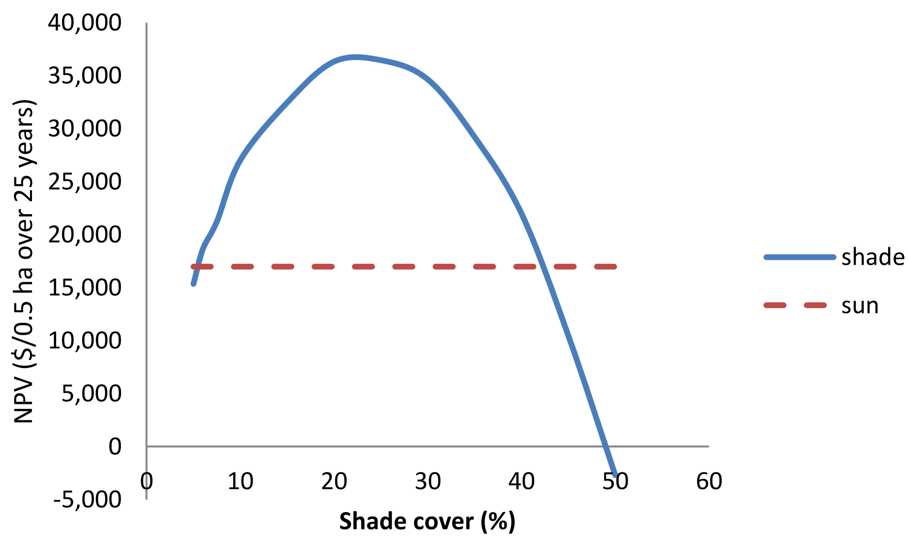


b. CBB infestation

Figure 4. Effect of shading on coffee farm expected net present values (ENPV) in a sun-grown and a shade-grown coffee system (data points are from Table 5; $p_{shade} = \$3.66/kg$).



a. No CBB infestation



b. CBB infestation