



Analysis

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



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ABSTRACT

Transitioning from intensive, sun-grown to shade-grown coffee systems is promoted as a promising ecosystem-based climate adaptation strategy. Intercropping shade trees with coffee shrubs can produce multiple ecosystem services. Depending on the shade cover levels, however, the joint production of these services might be complementary or competitive based on their impacts on coffee yields. We develop a computational, bioeconomic model to find the range of shade level for which a coffee farmer is better off under a shade-grown system compared to a sun-grown system, in the presence of coffee berry borer (CBB) infestations. We model the plant-level provision of shade-induced pest control services, crop growth services, and timber, and consider in the baseline case a net price premium for shade-grown coffee. Using parameters from coffee regions in Colombia, our baseline simulation results indicate that, in the presence of a CBB infestation, the expected net present values in the shade-grown system can be higher but only for shade cover levels between 11% and 34%. The optimal shading level is 25% in the baseline scenario. It increases to 27% for greater values of crop growth ecosystem services and decreases to 20% in the absence of a price premium for shade-grown coffee.

1. Introduction

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 crop 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 more intensive and costly pest and disease management strategies.

Farmers can adopt agricultural practices that minimize uncertainty in coffee production in tropical areas with rising temperatures through the managed provision of ecosystem services. Recently, intercropping

shade trees with coffee shrubs has been promoted as a rational, economically feasible, and relatively easy-to-implement ecosystem-based climate adaptation strategy (Lin, 2007; Jaramillo et al., 2011; FNC, 2014; 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 those encountered on sun-grown plantations (Johnson et al., 2010; 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 shrubs and by increasing the soil organic matter from leaf litter, among other mechanisms (Beer, 1987; Siebert, 2002). Third, shade-grown coffee systems provide farmers with an additional market-based ecosystem service, namely timber from shade tree harvest. For instance, in the American tropics, Spanish laurel (*Cordia alliodora* (Ruiz and Pavón) Oken), a native, 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

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premium for their coffee if their production practices comply with shade-grown certification requirements (Ferraro et al., 2005; Kitti et al., 2009; Barham and Weber, 2012; Rueda and Lambin, 2013). On the other hand, shade-grown coffee systems decrease yields because of lower coffee shrub densities and competition for sunlight (Soto-Pinto et al., 2000; Siebert, 2002). Finally, shade-grown systems entail additional costs related to planting and maintaining shade trees (Batz et al., 2005; Kitti et al., 2009).

In this paper, we develop a bioeconomic model of multiple ecosystem services provision where services can be complementary or competitive based on their joint impact on yields (Wossink and Swinton, 2007). We apply this model to the case of a smallholder coffee farmer managing his/her farm for the simultaneous production of CBB pest control services, crop growth services (soil fertility services), and timber production, in addition to the main output, coffee. 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 yield effects of high levels of shade cover. Finally, our model accounts for the value of timber and possible price premiums paid by buyers of shade-grown coffee. We simulate increased shade cover levels to identify ranges for which the economic and ecological benefits provided by shade trees justify the ensuing yield reduction and additional costs associated with shade-grown production systems. We also conduct sensitivity analyses on key ecological, economic, and management model parameters to test the robustness of results.

2. Modeling Ecosystem Service Provision

Ecological 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 a decisive characterization of these ecological production functions is a key barrier to incorporating ecosystem services into resource decision-making. Barbier (2007) reviews various economic methods for valuing ecosystem services and notes that the production function (PF) approach, compared to stated-preference survey-based 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 a 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 contribute to the ecosystem service economics literature by proposing a class of models that can be used to simulate the spatially-explicit, 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 output. We use cellular automata and individual-based (plant-level) models to specify the functional relationships between shade, temperature, pest infestations and coffee yield. By doing so, the ecological production functions are generated from the spatiotemporal ecological dynamics (e.g., pest dispersal dynamics) specified at the individual ecological unit level rather than at the population or ecosystem level. Such specification is adequate for modeling ecosystem services that are affected by land management decisions (see Railsback and Johnson, 2014 for pest control services, Brosi et al., 2008 and Keitt, 2009 for pollination services).

Modeling pest control and crop growth services provided by intercropping coffee shrubs and shade trees requires the modeling of pest dynamics and the impact of shade on yield at the coffee shrub 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 et al., 2011). In the case of shade-grown coffee, the probability of infestation for an individual coffee shrub is a function of whether neighboring plants are shade trees or coffee shrubs, and whether neighboring coffee shrubs are infested and at what level. 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). Cellular automata are dynamic models that operate in discrete space and time. Each cell is in one of two states (e.g., invaded or not, as in Epanchin-Niell and Wilen, 2012) which is updated according to a state equation. Cellular automata can be considered a special case of individual-based models. One of the advantages that an individual-based model offers over cellular automata is the ability to model cells or individuals in any finite number of states.¹ In both types of models, at each time step t , a cell computes its new state given its old state and that of neighboring cells at $t-1$ according to mathematical functions and algorithms that constitute state transition rules (Tsefatson and Judd, 2006; Wolfram, 1986). These rules can represent bottom-up stochastic processes (e.g., pest dispersal) or top-down interventions (e.g., management strategies).

We formally define the computational bioeconomic model first. Then, we use simulation experiments to calculate farm expected net present values (ENPVs) at increasing levels of shade cover and three levels of shade coffee price premiums. Subsequently, we solve for the optimal shade levels and identify the range of shade for which the ENPVs of shade-grown systems are greater than the ENPVs of sun-grown systems in the presence of a CBB infestation. Finally, we conduct sensitivity analyses on key ecological and economic parameters.

3. 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 and symptom progression), 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 on a coffee farm. G is a set of $I \times J$ 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 shrub. In a shade-grown system, each cell represents a coffee shrub 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 farm with 900 coffee shrubs. 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 farm with 3025 coffee shrubs.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 shrub and a zero if the cell holds a shaded coffee shrub. State $s_{i,j,t}$ is the infestation state vector of a coffee shrub. Vector \mathbf{P} , of dimension 4×1 , holds a 1 for the state that describes a coffee shrub's infestation state and zeros for the remaining three states. A coffee shrub can be either *Healthy* or *Infested* at a *low* (1–10%),

¹ See Heckbert et al. (2010) for a detailed discussion on how individual- or agent-based models relate to cellular automata and Judson (1994) for recommendations on when to use each type of model.

² Planting densities used here are equivalent to 1800 shrubs/ha and 6050 shrubs/ha for shade-grown and sun-grown, respectively. These densities are consistent with those reported in Duque and Baker (2003): 1000–2000 shrubs/ha for shade-grown coffee and 4000 to 7000 shrubs/ha for sun-grown coffee.

moderate (10–25%), or high (> 25%) level. The three levels of infestation refer to the percentage of berries on each tree that are infested with CBB (Jaramillo et al., 2013). State $a_{i,j,t}$ is a 9125×1 vector holding a 1 for a tree's age in days and a zero for the other ages.

In our model, time t progresses in discrete daily steps up to 9125 days (i.e., 25 years). A coffee shrub's gross revenue is known to the farmer at time t . The revenue from a cell $r(\tau_{i,j}, s_{i,j,t}, a_{i,j,t})$ depends on the type of tree occupying the cell ($\tau_{i,j}$) (determined by shading scenarios), its infestation state ($s_{i,j,t}$) (determined by the stochastic pest dispersal process), and its age ($a_{i,j,t}$) (deterministic variable). Coffee yield is a function of shrub-level shading level (*shade*) and shrub-level infestation intensity ($\tilde{y}_{s_{i,j,t}}$). If a cell is unshaded, its coffee yield is equal to the yield of a shrub in a sun-grown system y_{sun} , multiplied by the infestation-related yield reduction terms, where applicable. If a shrub is shaded, its yield (y_{shade}) initially increases beyond y_{sun} with the amount of shade in its immediate neighborhood (*shade*) due to greater soil fertility and water availability ($\beta_1 > 0$ in Eq. (1a)).³ Then, beyond a threshold, additional shade decreases yield due to competition for sunlight ($\beta_2 < 0$ in Eq. (1a)) (Soto-Pinto et al., 2000). Note that this quadratic specification implies non-constant returns to scale of shade. Infestation reduces coffee yields according to Eq. (1b): yield reduction equals 2%, 6%, and 20% when CBB berry infestation is *low* (1–10%), *moderate* (10–25%), and *high* (> 25%), respectively (Table 1, Duque and Baker, 2003).⁴ Mathematically,

$$y_{coffee} = (y_{sun} + \beta_1 shade + \beta_2 shade^2) * (1 - \tilde{y}_{s_{i,j,t}}), \beta_1 > 0, \beta_2 < 0. \quad (1a)$$

Coffee revenue, $r_{s,i,j,t}^{coffee}$, is a function of price ($p_{Healthy,i,j,t}$), yield ($y_{Healthy,i,j,t}$), and pest-related yield reduction ($\tilde{y}_{s_{i,j,t}}$) (Eq. (1b)). Mathematically,

$$r_{s,i,j,t}^{coffee} = p_{Healthy,i,j,t} y_{Healthy,i,j,t} (1 - \tilde{y}_{s_{i,j,t}}). \quad (1b)$$

The timber revenue from a cell occupied by a shade tree, $r_{a,i,j,t}^{timber}$, is a function of the age state only (Eq. (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 merchantable timber yield (y_{timber}) and price (p_{timber}).⁵ We assume that the farmer harvests timber at $t = T$ and consider the impact of an earlier harvest in the Sensitivity analyses section. Symbols, definitions, values and references for the parameters are presented in Tables 1, 2, and 3.

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

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

$$E(s_{i,j,t+1}) = P^T s_{i,j,t}, \quad (2a)$$

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

³ The amount of shade in a coffee shrub's immediate neighborhood is defined as the shade canopy cover at the coffee shrub level, as in Soto-Pinto et al. (2000). 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. The coefficient 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 tree density (i.e., number of shade trees/total number of trees) and shade canopy cover in Soto-Pinto et al. (2000).

⁴ The resulting damage function, defined as the coffee yield reduction for increasing levels of infestation prevalence, is S-shaped, with increasing marginal damages between 0 and 20% and decreasing marginal damages between 80 and 100%.

⁵ Here we only consider the value of timber (assuming 50% of total standing volume is merchantable). The Spanish laurel tree also provides pollination services and is planted for honey production, among other uses (Liegel and Stead, 1990).

Table 1
Coffee yield 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).

Infestation is spatially constrained by the farm's horizontal (Eq. (2b)) and vertical boundaries (Eq. (2c)) as follows:

$$(i - 1) \in \{1, \dots, I - 1\}; (i + 1) \in \{2, \dots, I\} \quad (2b)$$

$$(j - 1) \in \{1, \dots, J - 1\}; (j + 1) \in \{1, \dots, J - 1\} \quad (2c)$$

These spatial constraints are formulated by defining the set of indices that cell (i,j) 's within-column (Eq. (2b)) and across-column neighbors (Eq. (2c)) can have. They ensure that the infestation does not spread beyond the cells situated at the borders of the parcel. All boundaries are reflecting (i.e., when the infestation reaches the boundary of a grid, it can be bounced back inside it, according to Eq. (2a)).

We now describe how the infestation state transition probability matrix P governs the plant-level CBB dispersal. Coffee shrubs in state *Healthy* (H) are susceptible to CBB infestation. CBB attacks a *Healthy* coffee shrub 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-moderate* to state *Infested-high* happens with a conditional probability f . Mathematically, P can be expressed as follows⁶:

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

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

$$b = \Pr(s_{i,j,t+1} = I_{low} \mid s_{i,j,t} = H) = 1 - e^{-n_t \alpha(net_temp)} \quad (4)$$

In Eq. (4), n_t indicates the number of infested coffee shrubs among the eight neighbors of a coffee shrub in period t (Fig. 1). This type of neighborhood, usually referred to as the 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 shrub that is surrounded by healthy coffee shrubs with or without shade trees. The probability that it will get infested within the next time step equals zero because $n = 0$. If it has n infested neighbors, a tree-to-tree infestation occurs with temperature-dependent growth rate parameter $n_t \alpha(net_temp)$ where $\alpha(net_temp)$ increases with temperature according to $\alpha(net_temp) = \alpha_0 + \alpha_1 net_temp$, and where net_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 ($temp$) and the reduction in temperature provided by a shade tree ($temp_reduc$). Within a time step, the probability that a coffee shrub with n_t *Infested* neighbors stays in the *Healthy* state before transitioning to the *Infested-low* state is exponentially distributed, with rate $n_t \alpha(net_temp)$. In each time step (i.e., on any day during the production season), a random variable x_t determines whether a coffee

⁶ 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 $t + 1$).

Table 2
Baseline coffee berry borer (CBB) dispersal parameters.

Parameter	Description	Value	Unit	Sources
α	Temperature-dependent exponential probability rate parameter ^a	$\alpha(net_temp) = \alpha_0 + \alpha_1 net_temp$	Day ⁻¹	Jaramillo et al. (2009)
α_0	Intercept	-0.005689	Day ⁻¹	Jaramillo et al. (2009)
α_1	Slope	0.00381	Day ⁻¹	Jaramillo et al. (2009)
$temp$	Temperature (farm level)	24	°C	Jaramillo et al. (2009)
$temp_reduc$	Shade-induced temperature reduction (berry level)	3	°C	Jaramillo et al. (2009)
$L_1^{no\ shade}$	Average waiting time between I_L and I_M state, no shade.	15	Days	Johnson et al. (2010)
L_1^{shade}	Average waiting time between I_L and I_M state, under shade.	45	Days	Johnson et al. (2010)
L_2	Average waiting time between I_M and I_L state, no shade.	60	Days	Johnson et al. (2010) and Ruiz-Cárdenas et al. (2009).

^a $net_temp = temp - temp_reduc$.

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

Parameter	Description	Unit	Coffee production system	
			Sun	Shade
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	kg/tree/year ^b	n/a	Eq. (1a)
β_1	Yield-shade parameters ^c		n/a	0.0175
β_2			n/a	-0.0002
$p(s_{i,j,t} = Healthy)$	Price ^d	\$/kg	3.16	3.41
$c_{i,j,t}$	Production cost ^e	\$/tree/year ^b	1.28	1.28
Timber				
y_{shade}	Merchantable yield	Cubic inches/tree/year ^b	n/a	0.005
p_{shade}	Price ^e	\$/cubic inches	n/a	537
$c_{u_{i,j},0}$	Planting cost ^{a,b,c}	\$/tree	n/a	0.12
$c_{u_{i,j},t}$	Maintenance cost ^{e,f}	\$/tree/year	n/a	0.07
ρ	Discount factor	Year ⁻¹	10%	10%

n/a is not applicable. \$ is US dollars.

^a Parameter values from Chamorro et al. (1994).

^b Values are expressed per day in the model.

^c Parameters obtained from model calibration (see Section 3.2).

^d National Coffee Federation of Colombia, Price list, May 13, 2013.

^e Values are expressed in real terms.

^f Parameter value from Batz et al. (2005).

shrub transitions from the *Healthy* state to the *Infested-low* state. A *Healthy* coffee shrub that has n_t *Infested* neighbors is infested by the pest at time $t + 1$ if $x_t < 1 - e^{-n_t \alpha(net_temp)}$, where x_t is a random draw from $U \sim (0, 1)$. Conversely, the pest does not colonize the neighboring tree if $x_t \geq 1 - e^{-n_t \alpha(net_temp)}$. Note that we compare the random variable with the transition probability in each time step because the number of *Infested* neighbors n_t changes over time as a result of the pest spread, thus changing the probability that a coffee shrub receives the infection in each time interval. 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.

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

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

This probability also depends on a coffee shrub's neighborhood state. Coffee shrubs that have a mature shade tree in their

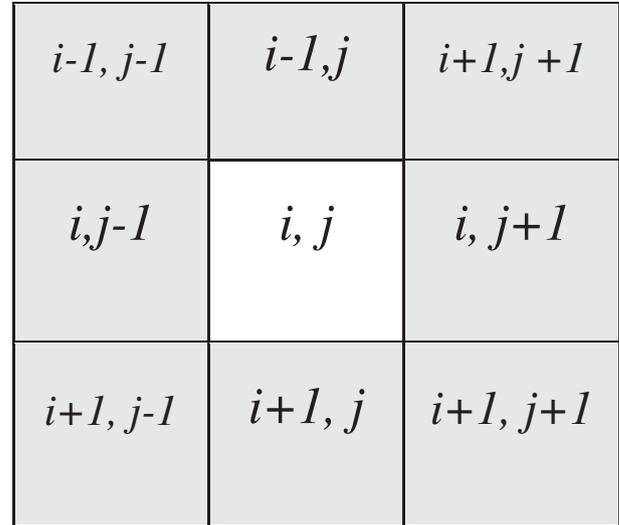


Fig. 1. Neighborhood of a coffee plant (i, j).

neighborhood reach the *Infested-medium* state with a greater waiting time ($L_1^{no\ shade} < L_1^{shade}$) than those who are not under shade (Johnson et al., 2010; Jaramillo et al., 2013). Period L_1 , the waiting time after a coffee shrub enters state *Infested-low* (I_L) and before it transitions to state *Infested-moderate* (I_M), is a random variable, exponentially distributed with fixed rate parameter $1/L_1$ that is equal to $1/L_1^{no\ shade}$ or $1/L_1^{shade}$ depending on whether the coffee shrub is unshaded or shaded, respectively.

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

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

As in Eq. (5), this probability depends on a coffee shrub's neighborhood state. Coffee shrubs that have a mature shade tree in their neighborhood never reach the heavily infested state (Jaramillo et al., 2013). For coffee shrubs 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 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 level. Each shading level is defined as the percentage of cells that have a shade tree over the total

number of cells on the grid and therefore translates into a binary decision for each cell (i, j) at the beginning of each simulation whereby $u_{i,j,0} = 1$ if a shade tree is planted and 0 otherwise for each (i, j) at $t = 0$. Once a shade tree is planted, it takes τ_{max} periods to reach maturity at which point it has an economic value and provides shade-induced ecosystem services to coffee shrubs in its neighborhood (by reducing conditional probabilities b , d , and f , Eqs. (4), (5), (6)), crop growth ecosystem services according to Eq. 1a, and timber at $t = T$.

The optimal shading strategy \mathcal{W}^* translates into a set of cell-level control variables $\{u_{i,j,0}\}$ that maximize ENPV over the time horizon. Letting E be the expectation operator over the random cell-level revenues $r(\tau_{i,j}, s_{i,j,t}, a_{i,j,t})$ and ρ^t the discount factor⁷ at time t (in days) where $t \in \{0, 1, 2, \dots, 9125\}$, the objective of a coffee farmer is to maximize the ENPV as follows:

$$\max_{\mathcal{W}} E \sum_t \rho^t \sum_{(i,j)} \{r(\tau_{i,j}, s_{i,j,t}, a_{i,j,t}) - c_{i,j,t} - u_{i,j,0} (c_{u_{i,j,0}} + c_{u_{i,j,t}})\} \quad (7)$$

subject to Eq. (2a) $E(s_{i,j,t+1}) = P^T s_{i,j,t}$.

The first expression in Eq. (7) represents the revenue generated by a cell (i, j) , which depends on its tree type ($\tau_{i,j}$, indicating a shaded coffee shrub and shade tree or an unshaded coffee shrub), infestation ($s_{i,j,t}$, indicating the infestation state and intensity of a coffee shrub) and age ($a_{i,j,t}$) states at time t . This term accounts for both coffee and timber revenues. The second term is the unit cost of coffee production $c_{i,j,t}$. The third term is the shade tree-related costs. If the farmer plants a shade tree in cell (i, j) at $t = 0$, then $u_{i,j,0}$ equals 1. This term accounts for the cost of shade tree planting, $c_{u_{i,j,0}}$; and for the cost of maintaining a shade tree through fertilization and pruning, $c_{u_{i,j,t}}$.

3.1. Model Initialization

All coffee shrubs are initialized as healthy and unshaded. At model startup ($t = 0$), depending on the shade level simulated, a percentage of unshaded cells are randomly chosen from a uniform spatial distribution $U(0, I^*J)$ to transition to the state shaded. Cells in the shaded state cannot transition back to the unshaded state. Coffee shrubs are initialized at planting and assumed not to bear fruit until year 4 (Eq. (1c)). The beginning of each simulation run represents the start of a calendar year. Coffee shrubs are initialized as *Healthy*. In September, when berries are ripe, a small percentage (0.7%) of the coffee shrubs 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 shrubs according to the state transition described in Eqs. (2a), (2b) and (2c) 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 re-infestation in the following September, when pest dispersal resumes (Jaramillo et al., 2006). We model this by letting coffee shrubs transition back to state *Healthy* (i.e., recovery) every year, at harvest. In each season, initial infestation is equal to the infestation prevalence at the end of the previous season (i.e., at harvest), reflecting the season-to-season re-infestation from residual berries on the ground or on the branches (Jaramillo et al., 2006).

3.2. Model Calibration and Parameterization

We calibrate Eq. (1a) by finding the values of β_1 and β_2 that generate the concave relationship between shade cover and per-shrub coffee yields 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) and consider lower and higher values in the Sensitivity analyses section. We choose a daily time step to be consistent with the time units of CBB dispersal parameters (Railsback and Johnson, 2014). Sun-grown and shade-grown production parameters are presented in Table 3.

4. Experimental Design

We design and implement experiments to produce ENPV observations for increasing shading levels. To solve the model, we incrementally allocate cells for shade-grown coffee and generate the corresponding ENPV values to obtain an ENPV function and find the shading level that maximizes it over the relevant domain of shading level (0–100%). Note that the 0% shading level corresponds to a sun-grown production system. Each experiment consists of a set of 100 simulation runs, over 9125 days (25 years), on a coffee farm of 900 coffee shrubs for the shade-grown coffee experiments and 3025 coffee shrubs for the sun-grown coffee experiments. We define shade levels as the percentage of cells that have a shade tree 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 (Somarrriba, 1992 and references therein). We, therefore, assign the location of shade trees in the shading experiments using random draws from a uniform distribution. 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). The model is written in Java and simulated using the software AnyLogic™ (XJ Technologies).

5. Results and Discussion

We first present results of the ENPVs of a sun-grown coffee farm and 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.

5.1. The Economics of Shade-induced Ecosystem Services With and Without CBB Infestation

We find that the expected net present values in the shade-grown system are higher than in the sun-grown system between shade levels of 11% and 34% in the presence of CBB infestations, and the optimal shade level is 25% (Fig. 2a). At the optimal shade level, the ENPV of the shade-grown system is 33% greater than that of a sun-grown system (the difference is \$6674/0.5 ha, or \$13,348/ha, over 25 years; Table 4). Below that shading level, pest control services, crop growth services, and timber are complementary based on their impact on coffee yield and consequently ENPVs. Beyond that level, the beneficial effects of pest control services and timber production are offset by reduced coffee shrub yields (according to Eq. (1a)) and increased production costs. Soto-Pinto et al. (2000) indicate that the negative effect of shade cover on coffee yields beyond a certain threshold is due to the coffee shrubs' sensitivity to sunlight (solid line, Fig. 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 system.

In the absence of CBB infestations, the optimal shade level is lower, at 20%, and the shade-grown coffee farm generates ENPVs that are 9% lower than under a sun-grown system (Table 4 and Fig. 2b). This result suggests that the higher economic performance of the shade-grown system in Fig. 2a is driven by its resilience to CBB infestations, i.e. pest

⁷ $\rho^t = \frac{1}{(1+r)^t}$, where r is the discount rate.

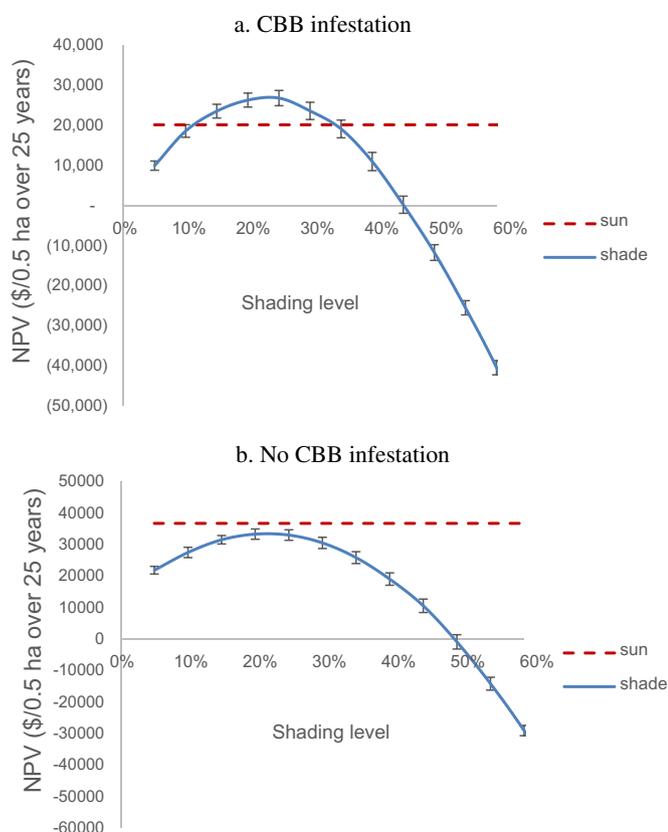


Fig. 2. Effect of shading on coffee farm expected net present values (ENPV) in a sun-grown and a shade-grown coffee system, with and without infestations (data points are from Table 4; error bars represent standard deviations).

Table 4

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

Coffee system	CBB		No CBB	
	ENPV ^b (\$1000/ha)	Percent change in ENPV ^a	ENPV (\$1000/ha)	Percent change in ENPV ^a
Sun-grown	20.1 (7.5) ^c	n/a	36.7 (0)	n/a
Shade-grown (% shade level)				
5	9.9 (1.2)	– 51%	21.8 (1.2)	– 41%
10	18.6 (1.6)	– 8%	27.5 (1.6)	– 25%
15	23.5 (1.7)	17%	31.5 (1.3)	– 14%
20	26.3 (1.7)	31%	33.3 (1.6)	– 9%
25	26.8 (1.9)	33%	33.0 (1.7)	– 10%
30	23.6 (2.2)	17%	30.5 (1.8)	– 17%
35	19.1 (2.2)	– 5%	25.8 (1.9)	– 30%
40	10.9 (2.3)	– 46%	19.0 (2.0)	– 48%
45	0.2 (2.1)	– 99%	10.5 (2.1)	– 71%
50	– 11.8 (2.1)	– 159%	– 0.9 (2.3)	– 103%
55	– 25.6 (1.8)	– 227%	– 14.2 (2.0)	– 139%
60	– 40.5 (1.8)	– 301%	– 29.1 (1.6)	– 179%
65	– 58.3 (1.8)	– 390%	– 46.0 (1.9)	– 225%
70	– 77.2 (1.5)	– 484%	– 65.4 (1.8)	– 278%
75	– 98.8 (1.5)	– 591%	– 86.7 (1.4)	– 336%

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.

^c Standard deviations in parentheses.

control services, rather than crop growth services and timber production. In the absence of CBB infestations, the maximum value of crop growth ecosystem services and timber provided by shade trees is not enough to offset the forgone coffee yields and greater production costs in a shade-grown system compared to a sun-grown system (Fig. 2b).

5.2. The Role of Price Premiums in Production System Decisions

Previous studies have estimated price premiums that are lower and higher than our baseline value (\$0.25/kg, or 8%). 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).⁸ Shade coffee certification programs seek to link environmental and economic goals through a price premium, as a payment for the ecosystem services provided by shade-grown coffee systems. Depending on the magnitude of this premium, it might or might not be enough to compensate a farmer for lower yields (Perfecto et al., 2005) and higher production costs (Gobbi, 2000) that ensue from the shade levels required under these programs. To understand the relationship between the price premium and the ENPV-improvement of shade-grown coffee over sun-grown coffee systems, we generate the main results 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%.

When there is no price premium for shade-grown coffee, the optimal shade is lower, at 20%, compared to 25% in the baseline case of a moderate price premium (Fig. 3). At that shade level, the difference in ENPVs between a shade-grown and a sun-grown system decreases to 4%, compared to a difference of 33% between the two systems in the baseline case. These results indicate that the ENPV improvement provided by a shade-grown system can critically depend on the presence of a positive net price premium.

When a farmer receives a net price premium of \$0.5/kg or 16%, the optimal shade level is 25%, as in the baseline case (Fig. 3). The difference in ENPVs between sun- and shade-grown coffee systems is \$14,380/0.5 ha (\$28,760/ha) over 25 years and represents a difference of 75%. Note that the optimal shade does not increase beyond 25% when we increase the shade level from the moderate to the high level, suggesting a limit to the shading level certification agencies might require farmers to have, even when farmers receive high premiums.

6. Sensitivity Analyses

We conduct sensitivity analyses to examine the effect of changes in the baseline values of model parameters on the optimal shading level and the corresponding ENPVs. The main goal of the sensitivity analyses to the ecological parameters is to test model robustness to small changes in parameter values, but in certain cases we also consider wider parameter value changes if they occur in the literature reported in the literature. We start with the model sensitivity analyses to the ecological production function parameters, including those related to CBB growth and pest control services (i.e., infestation state transition probability parameters, yield reduction, farm temperature and shade-induced berry-level temperature reduction) as well as those related to crop growth services (i.e., impact of shade on coffee yields). We then present results of model sensitivity to economic and management parameters, namely farm size, fixed production costs, discount rate, and timing of timber harvest. The analysis of model sensitivity to alternative economic and management parameters is relevant, given the existing differences in production systems and conditions.

⁸ The corresponding net premiums would be 1% and 20% for Colombia, 3.5% for Peru, and 10% for Ethiopia (assuming that certification costs amount to half of the premiums, as estimated in Gómez et al., 2011).

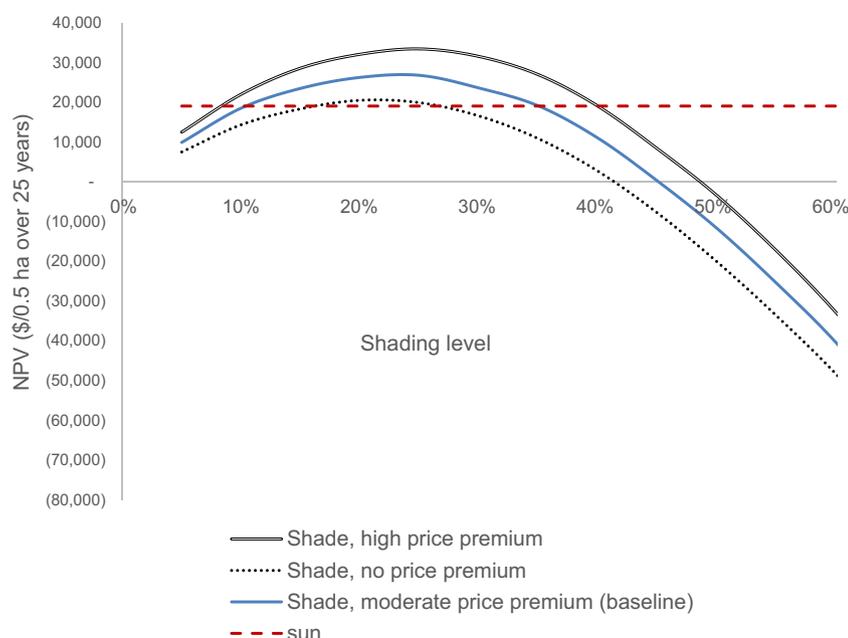


Fig. 3. Effect of net price premium on optimal shading level and coffee farm expected net present values (ENPV) in a sun-grown and a shade-grown coffee system. No price premium; moderate price premium, baseline (\$0.25/kg, or 8%); high net price premium (\$0.5/kg, or 16%).

6.1. Model Sensitivity to Ecological Production Function Parameters

We start by analyzing the model sensitivity to the initial infestation prevalence. We find that the optimal shading level is slightly lower than the baseline (24%) if the infestation increases to 1% or even to 6%. The difference in ENPVs between the new optimal shade levels and the baseline optimal shade level of 25% is around 2% in all cases. This suggests that the model's optimal shading level recommendation is mildly sensitive (in ENPV terms) to small increases in the initial infestation level. As reported in the previous section, however, if the infestation is 0%, the optimal shading level decreases to 20%; this larger decrease occurs because there are no pest control ecosystem service benefits to be captured in the case of no CBB infestations.

We consider the following ecosystem service production function parameters: the temperature-dependent infestation state transition probability parameters (parameter α_1 in the *Healthy to Infested-low* temperature-dependent transition probability b ; farm-level temperature, berry-level temperature reduction; parameter $L_1^{no\ shade}$ in the *Infested-low to Infested-medium* probability d ; and parameter $L_2^{no\ shade}$ in the *Infested-medium to Infested-high* probability f , Eqs. (4)–(6)) and the net temperature around the berries (parameter net_temp , Eq. (4)).

We find that for a lower value of the temperature-dependent CBB growth rate ($\alpha_1^{low} = 0.003429$, the lower bound of the confidence interval for this parameter in Jaramillo et al., 2009) the optimal shade decreases to 22%. For a larger parameter value ($\alpha_1^{high} = 0.004191$, the upper bound of the confidence interval), the optimal shading level is 23%. Adjusting the optimal shade recommendation from 25% (baseline) to 24% or 22% based on the lower and higher values of α_1 generates a negligible change in the ENPVs (2% and 1%, respectively). This result suggests that the model shading level recommendation is only modestly sensitive (in ENPV terms) to the changes in the temperature-dependent CCB growth rate parameter values considered (Table 5).

We consider lower and higher values of the temperature variable ($temp$). Likewise, we consider lower and higher values of the temperature reduction variable ($temp_reduc$).⁹ The optimal shading level remains at 25% for the higher temperature (25 °C) but decreases to 24%

⁹ In the baseline model, we use a temperature of 24 °C (the mid-range of the temperature range (20–27 °C) used in Jaramillo et al. (2009) to estimate the relationship between temperature and CBB growth rate) and a shade temperature reduction of 3 °C (the mid-point of the range of 2–4 °C reported in Jaramillo, 2005).

Table 5
Model sensitivity to ecological production function parameters.

Parameter	Optimal shading level (% shade trees)	ENPV (\$1000/0.5 ha)
<i>Initial infestation (%)</i>		
0	20%	33.3 (1.6) ^a
0.7	25%	26.8 (1.9)
1	24%	26.7 (1.9)
6	24%	26.5 (2.1)
<i>Temperature-dependent infestation rate, α_1 (day⁻¹)</i>		
0.003429	24%	27.7 (1.9)
0.00381	25%	26.8 (1.9)
0.004191	22%	26.3 (2.0)
<i>Temperature, $temp$ (°C)</i>		
23	24%	27.1 (2.0)
24	25%	26.8 (1.9)
25	25%	26.2 (2.1)
<i>Temperature reduction, $temp_reduc$ (°C)</i>		
2	25%	26.1 (1.9)
3	25%	26.8 (1.9)
4	26%	26.7 (2.0)
<i>Waiting time between I_L and I_M, no shade, $L_1^{no\ shade}$ (days)</i>		
7.5	25%	26.4 (2.1)
15	25%	26.8 (1.9)
30	25%	26.5 (1.9)
<i>Waiting time between I_M and I_H, no shade, $L_2^{no\ shade}$ (days)</i>		
45	25%	26.6 (1.7)
60	25%	26.8 (1.9)
120	25%	26.8 (1.8)
<i>Yield reduction parameters ($I_L; I_M; I_H$) (%)</i>		
1;4;13	25%	27.7 (2.1)
2;6;20	25%	26.8 (1.9)
3;9;30	21%	24.8 (1.8)
<i>Crop growth linear parameter, β_1</i>		
0.0150	19%	17.2 (1.7)
0.0175	25%	26.8 (1.9)
0.0200	27%	37.4 (2.2)
<i>Crop growth quadratic parameter, β_2</i>		
- 0.000350	23%	26.2 (1.8)
- 0.000175	25%	26.8 (1.9)
- 0.000088	25%	26.9 (1.9)

^a Standard deviations in parentheses.

for the lower temperature (23 °C). A lower (2 °C) value for the temperature reduction parameter does not affect the optimal shade solution, which remains at 25% whereas a higher temperature reduction increases the optimal shade to 26%. That is, a higher magnitude of temperature reduction increases the marginal pest control ecosystem service benefits of shade, which increases the optimal shade level. These results suggest that a lower shade would be optimal in less warm production regions and that more shade would be optimal if the shade tree planted generates greater shade reduction, everything else held constant. However, these one and two percentage point changes in optimal shade are not practical to implement with exactitude. Moreover, they are not economically meaningful: the resulting differences in ENPVs between the baseline optimum and the new optimums are < 1%.

In the case of the *Low to Moderate* and *Moderate to High* transition probabilities (d and f), we find that if the average waiting times between states $L_1^{no\ shade}$ and $L_2^{no\ shade}$ are shorter (i.e., infestation intensity and symptoms progress faster), ENPVs are lower as expected, but the optimal shading level remains at 25% (Table 5). Finally, we investigate the effect of changes in the value of yield reduction at these infestation levels. If yield reduction is lower (1%, 4%, 13% for the low, moderate and high infestation intensities, respectively), the optimal shading level remains at 25%. However, if yield reduction is higher (3%, 9%, 30% for the low, moderate and high infestation intensities, respectively), the optimal shading level decreases to 21%. The difference in ENPVs at 21% vs 25% shade is 3%, making the model's shading level recommendation most sensitive (in ENPV terms) to the yield reduction parameter, among the pest-related ecological parameters considered.

We now consider the crop growth ecosystem production function parameters (parameters β_1 and β_2 in Eq. (1a)). Parameter β_1 is shade tree-specific and represents the increase in coffee yield provided by the shade tree through ecosystem services such as an increased soil fertility and water availability. For a lower value of this parameter ($\beta_1^{low} = 0.0150$), the optimal shading level decreases to 19% and the ENPV decreases by 10% compared to a shading level of 25% for that parameter value. Importantly, the ENPV is 16% below the ENPV of a sun-grown system. A higher value of β_1 ($\beta_1^{high} = 0.020$) increases the optimal shading level to 27%. The ENPV increases by 2% compared to the baseline. A higher value of β_1 increases the marginal benefit of shading thus increasing the optimal level of shade, and vice versa. Larger diminishing returns to crop growth ecosystem services ($\beta_2^{high} = -0.00035$) reduce ENPVs by 3% and reduce the optimal shading level to 23% (i.e., a more negative β_2 decreases the marginal benefit of shading). Lower diminishing returns ($\beta_2^{low} = -0.00088$) increase ENPVs by < 1% and do not affect the optimal shade level.

In conclusion, among the ecological production function parameters, optimal shading level is most sensitive in ENPV terms to the parameter capturing the shade tree's impact on coffee yields (β_1) (27% optimal shade; 10% change in ENPV at new optimal shading level compared to the baseline), followed by the yield reduction parameter (20% optimal shade; 3% change in ENPV compared to the baseline). The sensitivity of the model results to the β_1 parameter highlights the importance of the choice of the shading tree species based on its impact on yield through ecosystem services such as soil fertility and water availability. The only ecological parameter value change that causes a shade-grown system to yield lower ENPVs than a sun-grown system is a zero initial CBB infestation level (Tables 4 and 5).

6.2. Model Sensitivity to Economic and Management Parameters

We study the effects of fixed costs, farm size, then discount rate, and timing of timber harvest, in that order. The baseline model does not account for fixed costs associated with converting a farm from a sun-grown to a shade-grown system. Ramirez and Soza (2000) report a fixed cost of \$2122/ha (in 2014 dollars) estimated by the Costa Rican Coffee Institute as an average for three different agroforestry systems. Their

Table 6
Model sensitivity to economic parameters.

Parameter	Optimal shading level (% shade trees) ^a	ENPV (\$1000/0.5 ha)
<i>Fixed costs (\$/0.5 ha)</i>		
0	25%	26.8 (1.9)
530	25%	26.2 (1.9)
1061	25%	25.7 (1.9)
2122	25%	24.6 (1.9)
<i>Grid dimensions (equivalent farm size in ha in brackets)</i>		
15 × 15 [0.1 ha]	22%	5.1 (1.6)
20 × 20 [0.2 ha]	23%	10.2 (1.5)
30 × 30 [0.5 ha]	25%	26.8 (1.0)
45 × 45 [1.1 ha]	25%	66.0 (2.0)
<i>Discount rate</i>		
4%	26%	43.4 (3.2)
10%	25%	26.8 (1.0)
15%	24%	19.6 (1.2)
<i>Timber harvest timing</i>		
Year 25	25%	26.8 (1.0)
Year 13	25%	29.0 (1.1)
Year 13, no price premium	20%	22.3 (1.4)

^a Standard deviations in parentheses.

estimate includes capital invested in the agroforestry system, depreciation of infrastructure and equipment, short-term credit, and managerial and administrative costs. We consider their average value (\$1061/0.5 ha), in addition to a lower (\$530/0.5 ha) and a higher value (\$2122/0.5 ha). The optimal shading level (unsurprisingly) remains at 25% (Table 6). The ENPV improvement over a sun-grown system decreases from 33% (baseline) to 31%, 28% and 23% for the low, average, and high fixed cost values considered.

While we consider a 30 × 30 grid in the baseline case, we generate simulation results for two smaller grids (15 × 15 and 20 × 20) and one larger grid (45 × 45) representing smaller and larger coffee farms, respectively. We find that the optimal shade is lower (22% and 23%) for the smaller farm sizes (15 × 15 and 20 × 20 respectively), whereas it remains at 25% for the larger (45 × 45) farms (Table 6). Importantly, we find that the shade-grown system in the smaller farms does not produce higher ENPVs compared to the corresponding sun-grown system. The ENPV improvement of the shade-grown system compared to the sun-grown system is -28%, -18%, 33%, and 103% for the 15 × 15, 20 × 20, 30 × 30, and 45 × 45 grid sizes, respectively. This result indicates that, among smallholders, it might be hardest for those with the smallest farm sizes to transition from a sun-grown to a shade-grown system and to comply with higher shading levels that are required for shade-grown certification. Note that grid sizes 15 × 15, 20 × 20, 30 × 30 correspond to farms that are less than a hectare, which is the farm size category that represents the majority of coffee farmers in Colombia (FNC, 2014). These results indicate that among the economic and management parameter value changes considered here, the economics of transitioning from sun-grown to shade-grown is most sensitive to farm size.

We find that a higher discount rate (15%) has the expected effect of reducing ENPV values and vice versa for a lower discount rate (4%). A higher discount rate decreases the optimal shading level from 25% to 24%, and a lower discount rate increases the optimal shade level to 26%. A smaller discount rate results in a more equal weighting of the immediate costs of planting and maintaining shade trees and the later ecosystem service benefits of shade trees, thus increasing the optimal shade level, and vice-versa. The difference in ENPVs between the 25% and 26% shade levels for this discount rate value is 2%. For all discount rates, transitioning from sun-grown to shade-grown remains ENPV-improving.

Finally, we test the model sensitivity to the timber harvest timing. We include a scenario where harvest takes place in year 13

($t = 4745$ days) rather than at the end of the time horizon (year 25). We find that harvesting timber earlier does not affect the optimum shade, which remains at 25%. This increases the ENPV to \$29,053, which is 8% higher than the baseline where harvest occurs in year 25. However, harvesting shade trees prematurely most likely disqualifies the farm from receiving the shade-grown coffee premium, in which case the optimal shading level decreases to 20%, and the ENPV decreases to \$22,339 (i.e., a decrease of 17% compared to harvesting timber in year 25).

7. Conclusions

Ecosystem-based adaptation imposes direct and opportunity costs that might leave a coffee grower worse off. We find that where CBB infestations are present, adopting shade-grown coffee systems can generate ENPVs that are substantially higher than those of sun-grown systems. Whether the transition from a sun-grown to a shade-grown system is ENPV-improving depends critically on the level of crop growth ecosystem services produced and the farm size. Increasing shade levels stimulates the simultaneous production of several ecosystem services (crop growth, pest control, and timber) that might be either competitive or complementary in the way they impact ENPVs. As a result, shade-grown systems are economically beneficial to a farmer only for particular ranges of ecological and economic parameter values.

Broadly, our results are consistent with previous empirical findings. They suggest that, unless certified coffee premiums are large, the best management practices required by certifiers might ensure profitability for coffee farmers mostly through yield rather than price premium channels (Valkila, 2009; Barham and Weber, 2012). 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 marginal bioeconomic analysis of shade-induced ecosystem service provision. By characterizing the ecological production functions in this model and recognizing complementarity and competition among the ecosystem services produced, we identify the range of shade cover that will not leave a farmer worse off under a shade-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 and depending on the shade tree used and farm size, this requirement might leave farmers with lower ENPVs under a shade-grown system than under a sun-grown system, unless they receive a large shade-grown net price premium (16%) that is far greater than reported values (1%, in Rueda and Lambin, 2013).

Model extensions might need to incorporate the risk of coffee rust infestations for applications in coffee ecoregions with high precipitation and humidity: Shading levels reported here and that are beneficial for controlling the CBB in ecoregions with low precipitation might be detrimental for controlling coffee rust infestations. In such regions, we expect the optimal shade levels to be lower than the levels indicated in this article, making it even harder to smallholders to afford shading levels required to access price premiums.

In this model, shading is randomly allocated over the landscape. There might be situations where investigation of the importance of spatial geometry and optimal landscape (Epanchin-Niell and Wilen, 2012; Chalak et al., 2017) is warranted such as when infestation initially starts from a border or a corner (e.g., due to a neighboring infested farm). In this case, there might be an optimal shading landscape consisting of locating shade trees in a more concentrated manner on that border or corner. This would be comparable to fire break strategies. Future work could apply the spatial-dynamic externality model of Atallah et al. (2017) to the model presented here to explore if alternative spatial geometries of shade are superior to spatially random shade allocation for those farms that are located near external sources of infestation. We hypothesize that such spatial configuration might be superior to random shade allocation in the first year as the infestation is

introduced but becomes less beneficial as the infestation establishes and re-infestation occurs in each year from within the farm.

This model provides an application for integrating bioeconomic decision-making tools with ecological production functions to assess the cost-effectiveness of ecosystem-based climate adaptation. 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 the provision of ecosystem services over space. For instance, it can be applied to other systems such as cocoa and tea production systems where shade cover is recommended simultaneously for climate adaptation (Verchot et al., 2007) and product differentiation (Millard, 2011) 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 framework used to study the spatial bioeconomics of ecosystem service provision remains.

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