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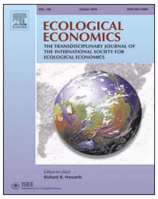

Analysis

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 (Tesfatsion 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 $\boldsymbol{P}$, 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%),

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[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.