

Bioeconomic Approaches to Sustainable Management of Natural Tropical Forests

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Abstract

Bioeconomic models are idealized representations of human-nature interactions used to describe how the decisions that people make regarding the harvest of biological resources affect the future condition of resource stocks and the flow of net economic benefits. This modeling approach posits an assumed goal or objective that a decision-maker seeks to optimize subject to a set of biological constraints. The power of this method derives from its ability to evaluate a wide array of alternative policy or management innovations over timescales that are radically longer than the timescales considered in many other approaches to economic analysis. In this chapter, we review techniques and applications of two complementary classes of bioeconomic models that have been used to analyze alternative strategies for sustainable use of tropical forests. First, continuous-time bioeconomic models have been used to derive dynamic policy prescriptions for optimally balancing tropical timber production and tropical forest conservation over very long time scales. Second, discrete-time bioeconomic models have been used to evaluate alternative on-the-ground timber harvesting strategies. Emerging threats associated with climate change could be addressed with bioeconomic models that consider the resilience of tropical forests to potentially catastrophic changes.

Keywords

Ecosystem service benefits; Optimal control; Non-market values; Social welfare; Time preference; Tropical forest conservation

Introduction

Sustainable management of tropical forests for timber, non-timber forest products, and other ecosystem services emerged as a global concern facing many of the world's developing countries during the past quarter century (Buschbacher 1990; Rice et al. 1997; Chazdon 1998; Bawa and Seidler 1998; Laurance 1999). One reason for the concern is the expansive footprint of tropical timber harvesting. In ITTO countries, for example, more than one-half of tropical forest area in permanent forest estate is designated as production forest (Blaser et al. 2011), and only about 4 % of that area is thought to be sustainably managed. Other evidence indicates that, between 2000 and 2005, at least 20 % of the tropical forest biome was undergoing some level of timber harvesting (Asner et al. 2009). There is an active debate about the degree to which tropical forests should be managed for a dominant use, e.g., parks in some locations and

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intensive timber production in other locations, versus multiple uses (Rice et al. 1997; Pearce et al. 2003; Putz 2004).

Exploitative, non-sustainable logging practices result from underlying economic and ecological conditions that lead to enormous profitability of initial harvests in primary forests, collateral forest damage caused by careless and destructive logging techniques, and slow biological growth of residual forest stands (e.g., Fisher et al. 2011; Johns et al. 1996; Macpherson et al. 2012; Pinard and Putz 1996; Rice et al. 1997). Although a recent meta-analysis of more than 100 scientific publications revealed that selectively logged forests retain 85–100 % of plant and animal species after harvest, timber yields available for subsequent harvests decrease by nearly 50 % after the first harvest (Putz et al. 2012). Selective logging also reduces carbon storage in biomass and soils (Foley et al. 2007; Putz and Pinard 1993; Pinard et al. 2000), and careless logging practices, combined with continued deforestation and anticipated changes in climate, may lead to tipping points resulting in dramatic changes in tropical forest structure and function during the twenty-first century (e.g., Barlow and Peres 2008; Malhi et al. 2009; Nobre and Borma 2009).

Recognizing the need to develop better regulations and management strategies to promote the sustainable use of tropical forests, economists have developed analytical models to help decision-makers evaluate the streams of future forest benefits resulting from alternative harvest regimes. Models that optimize public or private economic objectives (e.g., social welfare or profit maximization) subject to constraints describing dynamic biological processes (e.g., forest growth or land use change) are generally referred to as bioeconomic models. In general terms, these models are idealized representations of human-nature interactions that describe how the decisions that people make today regarding the consumption of biological resources (e.g., timber) affect the future condition of resource stocks (e.g., timber, carbon, biodiversity) and the flow of net economic benefits. The power of bioeconomic modeling derives from its ability to evaluate a broad set of potential management or policy innovations over very long time scales.¹ Although significant policy insights have been gained through empirical bioeconomic analysis, these models have generally not been implemented by on-the-ground management systems.

To help develop intuition regarding the strengths and limitations of the bioeconomic modeling framework for management of tropical forests, we present a brief primer on the key characteristics of two complementary approaches. Continuous-time (C-T) bioeconomic models have been used to derive time-varying policies for optimally balancing tropical timber production and forest conservation. In contrast, discrete-time (D-T) bioeconomic models have been used to evaluate alternative on-the-ground timber harvesting strategies. In section “[Continuous-Time Bioeconomic Models of Tropical Forests](#),” we describe how to construct a continuous-time optimal control model and derive the necessary conditions for maximizing social welfare derived from tropical forests over the very long run when both timber and non-timber forest outputs count. We also review specific tropical forestry applications using this modeling framework and provide an example in the [Appendix](#). This is followed (in section “[Discrete-Time Bioeconomic Models of Tropical Forests](#)”) by a description of how to construct a discrete-time optimization model subject to constraints on tropical forest growth using matrix population models. We subsequently review literature that uses discrete-time analysis to characterize optimal management of tropical forests. In section “[Conclusions and Emerging Research Directions](#),” we present our conclusions

¹Bioeconomic models for uneven-aged management of tropical forests are fundamentally different from the standard Faustmann model for determining the optimal rotation age of even-aged stands. This is because bioeconomic models optimize the entire path to a stationary solution, and each stage along the optimal path is characterized by a set of dynamic first-order (necessary) conditions. In contrast, the Faustmann model is characterized by a static first-order condition that prescribes optimal harvest timing.

and a list of ideas on how bioeconomic models may be adapted to improve the analysis of emerging issues in tropical forest sustainability.

Continuous-Time Bioeconomic Models of Tropical Forests

C-T bioeconomic models of tropical forest use and conservation have been reported in the literature for nearly a quarter century. This approach to analyzing optimal intertemporal use and conservation of renewable resources was initially articulated by Clark (1976) using an advanced mathematical framework known as optimal control theory.² To demonstrate the underlying logic of this approach, we describe the steps used to construct and interpret a model from the perspective of a social planner who cares about both timber and nonmarket ecosystem services produced by tropical forests.

Specify the Objective Function and Constraints

The construction of a bioeconomic (optimal control) model for tropical forest applications begins by specifying the objective function to be optimized along with a set of biological constraints. The objective function depends on the specific issue under investigation. Here we consider a social welfare function that recognizes the importance of both commodity production and the provision of nonmarket ecosystem services from tropical forests. The specification of the constraint set likewise depends upon the issue under investigation. In the example we develop here, the constraint is the biological growth of tropical forests.

The objective function for C-T dynamic optimization models is commonly the sum of a flow of (net) benefits from the present to the infinite future so that the behavior of the system over a very long time span can be considered. This time frame is appropriate for studying tropical forests because benefits such as biodiversity conservation or carbon sequestration will likely remain of critical importance to many generations in the future. However, a pragmatic issue stemming from the summation of (positive) net benefits over an infinite time span is that the simple summation of those net benefits will likewise be infinite.

By convention, most economists have avoided this problem by ascribing a lower value to benefits occurring in the future through a constant exponential discount rate (δ). However, a constant discount rate has the effect of trivializing potentially enormous economic impacts that could occur in the next one or two centuries, such as the effects of climate change on tropical forest structure and function. An alternative is to allow the discount rate to be a decreasing function of time, $\delta(t)$, and to approach zero as time approaches infinity. This approach is consistent with a growing body of empirical evidence (e.g., Harvey 1994; Heal 2005). As discussed below, the use of a declining discount rate gives greater weight to future generations and therefore is often considered to improve intergenerational equity.

The conventional “utilitarian” social welfare maximization problem can be written:

$$\max W = \int_0^{\infty} [c_t(h_t) + b_t(x_t)] e^{-\delta t} dt \quad (1)$$

where social welfare (W) is maximized from the present time ($t = 0$) to the infinite future ($t = \infty$). The in situ tropical forest stock (x_t) is the “state” variable, which could be disaggregated by timber species groups

²A more recent treatment of this topic is found in Heal (2005) who also provides an excellent review of alternative approaches to studying intertemporal welfare economics.

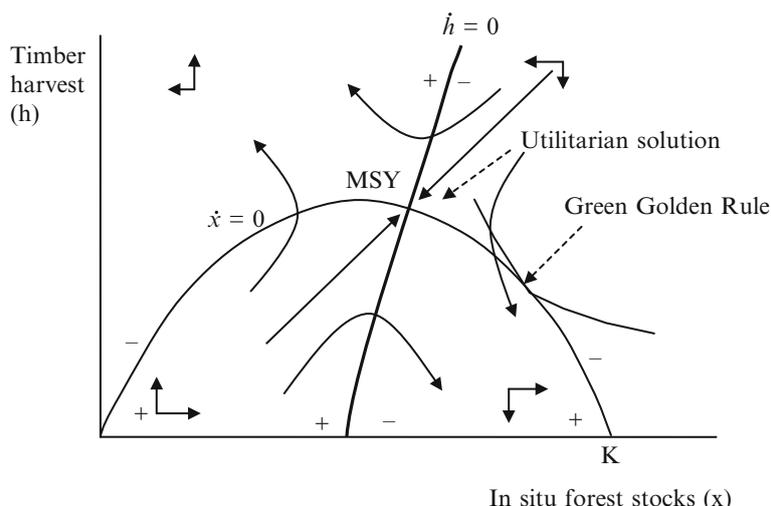


Fig. 1 C-T bioeconomic model of tropical forest harvesting and conservation showing the long-run equilibrium values associated with a utilitarian solution and the Green Golden Rule. Curved arrows depict the dynamics of the system away from equilibrium

(Montgomery and Adams 1995; Kant and Shahi 2013). Consumption value (c_t) is a function of the “control” variable h_t , which is harvest of the in situ stock. Ecosystem service benefits (b_t) are derived from the in situ forest stock. Social welfare is discounted at a constant rate δ ($\delta > 0$). To simplify notation, we will henceforth drop the time (t) subscript.

Social welfare is maximized subject to a biological constraint describing tropical forest growth. In the C-T bioeconomics literature, it has been common to specify a logistic growth function, although other functional forms could be used (e.g., Clark 1976, pp. 16–17). If $G(x)$ is logistic, then forest stocks are limited by the ecosystem carrying capacity (K) and the maximum sustained yield (MSY) equals $K/2$ (Fig. 1). Because tropical forest growth conditions may change over time, due to factors such as climate change and the cumulative impact of forest harvesting, the underlying arguments of the biological growth function (such as K and MSY) may likewise change. However, we do not explicitly consider that level of complexity here. Rather, we simply require that $G(0) = 0$ and $G(K) = 0$ and represent the change in forest stock over time (\dot{x}) as a general function consisting of two arguments:

$$\dot{x} = G(x) - h \tag{2}$$

where $G(x)$ is the natural growth of the aggregate stock x , h is defined as above, and the dot notation refers to the derivative of that variable with respect to time.

Use the Maximum Principle to Find the First-Order Necessary Conditions

The key result needed to develop an optimal control (bioeconomic) model is the maximum principle associated with the Russian mathematician L. S. Pontryagin (e.g., Chiang 1992). The maximum principle relies upon the specification of the Hamiltonian (H) function which is used to find the first-order necessary conditions. The H function is composed of the integrand of the objective function, the constraint, and a new variable, λ , which is known as the costate variable (or shadow price for in situ forest stocks):

$$H = e^{-\delta t}[c(h) + b(x)] + \lambda e^{-\delta t}(G(x) - h) \tag{3}$$

The first-order conditions for this problem are obtained by taking the derivative of H with respect to the control variable (h) and the state variable (x), subject to the equation of motion of the state variable (Eq. 2). Assuming an interior solution, the necessary condition for optimal harvests is

$$\frac{\partial H}{\partial h} = c'(h) - \lambda = 0 \quad (4)$$

where the prime ($'$) indicates the first derivative. This expression states that optimally, at every given time t , timber is harvested so that the consumption value from harvesting one more unit equals the value (shadow price) of maintaining one more unit in the ecosystem. It is important to recognize that the shadow price of the marginal unit of in situ forest stock (λ) represents the contribution of that unit to (discounted) social welfare (W) arising from its future productivity.

Given this interpretation of the shadow price of in situ forest stocks, it is straightforward to view the maximum principle from a capital theoretic perspective. In particular, we can now see that the Hamiltonian expression (Eq. 3) is composed of two sources of value contributing to W . First are the dividends arising from timber harvesting and the provision of ecosystem services in any time period t . Second is the value derived from investing in situ forest stocks that will provide dividends in the future. Consequently, the first-order necessary conditions describe how timber harvesting rates must be chosen to maximize the total capital value of tropical forests over time.

The next first-order necessary condition describes the equation of motion for the shadow price variable:

$$-\frac{\partial H_c}{\partial x} = \dot{\lambda} - \delta\lambda = -(b'(x) + \lambda G'(x)) \quad (5)$$

The Hamiltonian in this equation has been modified to reflect the current value (i.e., undiscounted value) of the Hamiltonian (H_c), which simplifies the process of taking derivatives (e.g., Chiang 1992, pp. 210–211). This transformation was not necessary in the derivation of Eq. 4, as the exponential term ($e^{-\delta t}$) canceled out of the expression (because it is a constant for any given t). The interpretation of Eq. 5 is made more intuitive by rearranging the expression to read

$$\dot{\lambda} = \lambda(\delta - G'(x)) - b'(x) \quad (6)$$

Now we see that the rate of change in the shadow price of in situ tropical forest stocks is equal to the difference between the opportunity cost of holding on to a marginal unit of stock (where the lost interest on other investments is compensated to a degree by biological growth) and the marginal social value of that unit (realized as nonmarket ecosystem services) (e.g., Barbier and Rauscher 1994).

Finally, in addition to the conditions shown in Eqs. 4 and 5, optimal timber harvests must obey the equation of motion for the state variable, as given by Eq. 2 above.

Examine the Stationary Solution

Having obtained the first-order necessary conditions for optimal timber harvesting, the next step is to examine the long-run stationary solution. By definition, a stationary solution to the dynamic optimization problem is sustainable because the volume of timber harvested is equal to timber growth:

$$G(x) = h \quad (7)$$

Clearly, if harvest exceeded growth, then forest stocks would decline over time, eventually resulting in

deforestation ($G(0) = 0$). On the other hand, if growth exceeded harvest, then forest stocks would increase over time, eventually allowing greater harvest levels.

A stationary solution occurs only when the shadow prices of in situ forest stocks are stable over time, $\dot{\lambda} = 0$ in Eq. 5. Using the equality shown in Eq. 4, we can substitute $c'(h)$ for λ . By rearranging the resulting expression, we find that

$$\frac{b'(x)}{c'(h)} = \delta - G'(x) \quad (8)$$

The expression on the left-hand side of Eq. 8 is the marginal rate of substitution between the utility derived from maintaining in situ forest stocks and the utility derived from the consumption of tropical timber. At the optimal stationary solution, this value is set equal to the discount rate minus the marginal growth rate of tropical forests.

Particular attention has been given to configurations of the economy that maximize sustainable utility derived from renewable resources. By setting the discount rate to zero ($\delta = 0$), maximum sustainable utility is found where the marginal rate of substitution between forest stocks and timber consumption equals the marginal rate of transformation of forest stocks into timber consumption:

$$\frac{b'(x)}{c'(h)} = G'(x) \quad (9)$$

This point of tangency between $b'(x)/c'(h)$ and $G'(x)$ is known as the Green Golden Rule (Chichilnisky et al. 1995) and occurs where in situ forest stocks are greater than the level required to produce the MSY (Fig. 1).³

However, when the opportunity cost of capital ($\delta > 0$) is included in Eq. 8, society needs to be compensated for that cost by a higher growth rate of tropical forests. This can be accomplished by reducing forest stocks toward the level required to produce the MSY. Further, if $\delta > 0$ and no weight is given to the value of standing forests in the objective function, then the optimal solution is described by $\delta = G'(x)$ and the optimal timber harvest will reduce stocks below the MSY level (e.g., Barbier and Rauscher 1994; Montgomery and Adams 1995). If the discount rate exceeds the marginal forest growth at all possible forest stock levels, then forest stocks may be entirely liquidated, even without considering the value of alternative land uses (e.g., Rice et al. 1997). Thus, we can see that the rationale for protecting tropical forests rests on both the value of in situ forest stocks for the production of timber and non-timber ecosystem services and a social discount rate that is less than the discount rate typically used by private enterprises. In the [Appendix](#), we present a numerical example that illustrates the effect of alternative interest rates (δ) on the optimal forest stocking using an example simulated for the Tapajós National Forest in the Brazilian Amazon.

³The original formulation of this problem sought to maximize the weighted sum of the utilitarian problem (as described above) and a term representing long run utility as time approaches infinity (Chichilnisky et al. 1995). The difficulty with this formulation is that it is always possible to postpone the time at which the long run solution is attained. However, the problem does provide a path for attaining the Green Golden rule if the constant discount rate (δ) of the utilitarian problem is replaced with a time-varying discount rate ($\delta(t)$) that approaches zero as time approaches infinity (e.g., Heal 2005).

⁴For the interested reader, the general approach is to linearize the system around the stationary solution and then calculate the eigenvalues of the linearized system (e.g., Conrad and Clark 1987).

Examine the Dynamics of the System

The final step in the analysis of a dynamic bioeconomic system is to examine the behavior of the system away from the stationary solution. The mathematics associated with a complete description of this step are rather advanced and cannot be adequately covered here.⁴ However, we provide a more intuitive explanation using what is known as a “phase diagram.”

In our example, the axes of the phase diagram are timber harvest (on the vertical axis) and in situ forest stocks (on the horizontal axis). The two main curves shown in Fig. 1 represent the subset of points where the control variable and the state variable are each stationary. In our example, in situ forest stock is stationary ($\dot{x} = 0$) along the dome-shaped curve representing the logistic growth function. Along this curve, $G(x) = h$ (see Eq. 2). Likewise, we plot a stationary curve for the level of timber harvest ($\dot{h} = 0$), which can be shown to have a positive slope in the plane (e.g., Barbier and Rauscher 1994; Heal 2005). The intersection of these two curves is the intertemporal equilibrium representing the utilitarian steady-state solution.

The dynamics of the tropical forest system away from intertemporal equilibrium are investigated by examining what is known about the signs (+ or –) of \dot{x} and \dot{h} (which indicate the direction of change) and the size of those derivatives (which indicate the speed of change). Beginning with the tropical forest growth function (\dot{x}), we can see when timber harvest is less (more) than growth, timber stocks will increase (decrease) because growth exceeds (is less than) harvest. These movements are recorded in the diagram by including a “+” sign below and a “–” sign above the $\dot{x} = 0$ curve. We have also drawn (small) rightward-pointing arrows below the curve and (small) leftward-pointing arrow above the curves to indicate the direction of movement.

The direction of movement of timber harvests away from equilibrium is a bit more complicated to derive. Begin by differentiating the first-order condition shown in Eq. 4 with respect to time, and then substitute for the resulting $\dot{\lambda}$ the expression shown in Eq. 5. Next, by substituting $c'(h)$ for λ (also from Eq. 4) and rearranging the expression, we find that

$$\dot{h} = \frac{c'(h)[\delta - r'(s)]}{c''(h)} - \frac{b'(s)}{c''(h)} \quad (10)$$

where the double prime (") represents the second derivative. When in situ stocks are low, we can expect that $\delta - r'(s) < 0$ and small (because the marginal growth rate will exceed the discount rate by only a small amount) and the first expression in the numerator on the right-hand side of Eq. 10 will be positive. Because we expect the denominator of this expression to be negative (due to diminishing marginal utility), we likewise expect the ratio to be small and negative. Looking at the second expression on the right-hand side of Eq. 10, we expect $b'(s)$ to be large and positive when forest stocks are low (because marginal ecosystem service benefits are large and positive when those services are rare). Consequently, when forest stocks are low, we anticipate that the sum of these expressions will be positive. Similar logic can be used to determine that when forest stocks are large, the sum of the two expressions will be negative. Thus, these movements are recorded in the diagram (Fig. 1) by including a “+” sign to the left of $\dot{h} = 0$ and a “–” sign to the right of the $\dot{h} = 0$ curve. We have also drawn (small) upward-pointing arrows to the left of the curve and (small) downward-pointing arrow to the right of the curve to indicate the direction of movement.

Combining the movement of nonstationary points into two-dimensional “streamlines” (the curved arrows in Fig. 1), we can plot the trajectory of the system from any point in phase space (only a few of the streamlines are drawn). The tropical forestry system that we have described results in what is known as a saddle-point equilibrium in which two stable arms (or separatrices, shown in Fig. 1) move toward the intertemporal equilibrium. However, two stable arms (not shown, but implied by the streamlines) lead away from the intertemporal equilibrium, indicating that the stationary equilibrium is unstable in those

Table 1 Continuous-time bioeconomic studies related to tropical forests

Authors	Subject	Objective function
Ehui and Hertel (1989)	Tropical deforestation	Present value of profit from forestry and agriculture
Barbier and Rauscher (1994)	International trade and tropical deforestation	Present value of future social welfare
Kant (2000)	Forest technology and institutions	Net social value
Sohnngen and Mendelsohn (2003)	Forest carbon sequestration	Abatement cost + damages
Potts and Vincent (2007)	Multispecies ecosystems	Net private timber value
Kant and Shahi (2013)	Timber harvest and ecosystem services	Long-run social utility

directions. The only way to arrive at the stationary equilibrium is to get on a stable arm (separatrix) moving toward the stationary equilibrium, observe changing conditions, and make necessary adjustments to stay on the stable arm. This is called a closed-loop control policy (e.g., Conrad and Clark 1987). In general, if the initial level of in situ forest stocks is less than (greater than) the optimal stocking level, then both forest growth and harvest are increased (decreased) until the stationary solution is attained.

Applications of the Continuous-Time Bioeconomic Model to Tropical Forests

Although the C-T bioeconomic model has seen many applications in other fields of renewable resource economics (e.g., fishing), there are relatively few applications specific to tropical forests (Table 1). Two early applications of an optimal control model applied to tropical forests considered the issue of deforestation. Ehui and Hertel (1989) evaluated factors reducing forest stock in the mixed forest-agricultural landscape of Côte d'Ivoire. At the time, the original 16 million ha of tropical rainforest in the country had been reduced to about 3.4 million ha. The objective function was specified to maximize the present value of society's welfare as a function of the profits available from forestry and agriculture and was subject to constraints on the profitability of these alternative land uses and on the rate of deforestation. Perhaps not surprisingly, the results showed that optimal forest stocks increase with increased returns to forest enterprises relative to those in agriculture. Further, the optimal forest stock was found to be most sensitive to the discount rate used in the optimization model.

In a second application of optimal control theory, the impact of trade interventions on deforestation was evaluated using a general (i.e., not location specific) bioeconomic model in which a tropical forest country seeks to maximize the present value of utility specified as a function of tropical logs harvested (some portion of which provide direct consumption benefits and some portion of which are exported to finance the consumption of imported goods) and the in situ forest stock (Barbier and Rauscher 1994). The change in forest stocks was specified using a natural forest growth function and a fixed rate of deforestation per volume of timber harvested. Several of the results in this paper are consistent with the results we report above for the utilitarian model specification. The authors also found that trade interventions are clearly second-best policies and that a more effective way to reduce tropical deforestation and increase conservation is through direct international transfers. We note that although it has been demonstrated that people living in the northern hemisphere are willing to pay substantial amounts to protect tropical forests (Kramer and Mercer 1997; Horton et al. 2003), actual payments for preventing the degradation and loss of tropical forests have been much less than these willingness to pay studies suggest (Pearce 2007).

The issue of forest carbon storage and sequestration has also been studied with C-T bioeconomic models. For example, Sohnngen and Mendelsohn (2003) developed a model that sought to minimize the sum of carbon abatement costs and climate-related damages over time subject to a constraint on the rate of change of carbon stocks, including forest sequestration. A large empirical model was developed using

inputs derived from other available global models of timber supply, carbon prices, and damages. They concluded that global forests could account for about one-third of total carbon abatement, with tropical forests responsible for two-thirds of that amount. However, they found that carbon sequestration in forests is more costly than generally appreciated due to systematic impacts on the prices of land and timber.

Another key policy issue is the devolution of property rights from governments to local communities, who now own or control nearly one-third of forests in developing countries (Rights and Resources Initiative 2012). The standard bioeconomic model described in detail above focuses attention on the dynamics of the natural system but does not explicitly consider the dynamics of the social system. One way to incorporate socioeconomic dynamics into these models is by recognizing that forest regimes (i.e., institutional arrangements) are functions of evolving social forces. This perspective has been formally analyzed in an optimal control model in which a decision-maker seeks to optimize the net present value of timber and non-timber forest products produced in developing economies subject to constraints on the dynamic behavior of the biological-social system (Kant 2000). The choice of optimal forest regime (the control variable) is found to depend upon a suite of socioeconomic factors that continually evolve, such as the degree of local dependence upon forest resources and the heterogeneity of local communities. Thus, this paper suggests that forest planning and management decisions need to adapt to evolving socioeconomic factors as communities in developing economies move through different phases of economic growth.

One limitation of the Green Golden Rule described above is that it does not differentiate between the multiple species that comprise renewable resource stocks. This shortcoming has been addressed by modeling the biological growth of multiple forest species interacting over time (Kant and Shahi 2013). In this approach, forest species are placed into species groups, and the Green Golden Rule (Eq. 9) is altered so that necessary conditions are expressed for each group. It is shown that the necessary conditions for each species group need to be adjusted so that the marginal rate of substitution between timber and non-timber benefits within each group equals the marginal rate of transformation of forest stocks into timber consumption adjusted for the interaction in biological growth rates between species groups. Although this enhancement adds complexity to the interpretation of the model, it recognizes that different forest species provide different social benefits (such as timber and non-timber forest products) and that the harvest of some species can enhance (or deter) the growth of other species.

Although all C-T bioeconomic models specify the temporal dynamics of a biological system, these models can also be used to analyze dynamic relationships over both time and space. For example, Potts and Vincent (2008) considered how spatial harvesting patterns affect the persistence or extinction of tree species in multispecies ecosystems. By parameterizing the ability of trees to colonize a vacant site (e.g., number and spatial dispersion of propagules) and to compete with neighboring trees (e.g., shade tolerance), a spatiotemporal multispecies meta-population model was developed and used to establish the set of constraints faced by a logging firm seeking to maximize net present value of timber harvests over the very long run. The results of this model show that when commercially valuable trees are uniformly harvested across a species diverse forest matrix, the species at greatest risk of extinction are the non-harvested trees that do not compete well relative to the harvested species. This contrasts with the case where timber harvests are concentrated in specialized management areas. In this case, the greatest risk of extinction accrues to the non-harvested top competitor species (as they are considered to be poor dispersers). This is a significant risk only if the intensively managed area equals or exceeds the area occupied by the top competitor in the original, undisturbed forest habitat.

Discrete-Time Bioeconomic Models of Tropical Forests

In contrast to the C-T bioeconomic models in which the biological constraints and necessary conditions appear as systems of differential equations, D-T bioeconomic models are specified using systems of difference equations. This permits the models to be solved using numerical methods. This framework provides a distinct advantage when the problem at hand consists of several control variables or multiple constraints. Further, as this modeling approach requires empirical parameterization of the objective function and constraints, the results are reported in quantitative terms, in distinct contrast to the descriptive results that are typical of C-T bioeconomic models (but, for a counterexample, see Sohngen and Mendelsohn 2003). However, limitations on the availability or quality of data available for specifying either the economic or biological parameters of the model often limit interpretation and, specifically, prevent any generalizations beyond the immediate study area.

In this section, we first describe the steps that are required to conduct a D-T bioeconomic analysis and then review studies that have used this approach to analyze specific management issues.

Specify the Objective Function

As with C-T models, construction of a D-T bioeconomic model begins by specifying the objective that a decision-maker would like to optimize. Unlike C-T models that often frame the objective from the perspective of a social planner who is concerned with maximizing the combined benefits of timber production and non-timber ecosystem services provided by in situ forest stocks, D-T bioeconomic models generally specify the objective from the perspective of a decision-maker who is seeking to maximize a financial measure of the returns from timber harvesting. This is more compatible with the quantitative nature of D-T bioeconomic models and the general lack of reliable data that could be used to specify the economic value of non-timber ecosystem services. As described below, concerns regarding biodiversity or other ecological benefits of in situ forest stocks are included in D-T models via the constraints.

A typical objective function could be specified as

$$\text{Max NPV} = \sum_{t=0}^T \frac{1}{(1+r)^t} \left[\sum_i (P_i - C) h_{it} - F \right] \quad (11)$$

where r is the discrete (e.g., annual) discount rate, P_i is the market value of timber species group i , C is the variable cost of harvest, h is the harvest volume of species group i , F is the fixed cost of harvest, t is the time period, and T is the terminal time. Calculation of the net present value (or land expectation value over an infinite time horizon) derived from tropical timber harvesting requires the analyst to assign a value for the rate of time preference. Unlike in C-T models specified from the perspective of a social planner, who may use a low or declining social discount rate, a constant rate of time preference that reflects general business conditions is typically used in D-T bioeconomic models.

We have specified the time period for analysis to extend from the present ($t = 0$) to some specified period in the future (T). This specification is used if the analyst is concerned with economic returns from a few cutting cycles. Although it is possible to extend the analysis far into the future, a constant exponential discount rate will cause economic benefits received after several cutting cycles to become empirically trivial. We also note that it is possible to include anticipated changes in timber prices or costs in the model specification if information is available to guide that decision.

Specify the Constraints

A major difference between C-T and D-T bioeconomic models of tropical forests is the specification of the constraint set. In contrast to the very general (e.g., logistic functional form) models used to characterize the biological growth of tropical forests in C-T models, D-T models typically rely upon empirically driven specifications of “matrix models” of forest growth and yield. This powerful class of models was first described for animal populations (Leslie 1945, 1948) and later modified to describe growth and yield in managed forests (Usher 1966). Although these early model formulations were based on the untenable assumption that populations grow exponentially in an unbounded fashion, this problem was addressed by introducing density-dependent recruitment of seedlings which effectively set an upper limit on forest growth (Buongiorno and Michie 1980). This modeling framework has been subsequently used in many studies, and applications to tropical forest bioeconomic models are described below.

The construction of a matrix model requires measurements of trees occupying specified size (diameter) classes – possibly in different species groups – at multiple points in time so that the growth of an entire forest stand can be projected into the future. The trees in each size class remain within that class, move to a larger size class, or die during the next period. This collective biological dynamic is projected based on the assumption that the transition probabilities only depend upon the current state of the system. A recruitment (the number of live trees growing into the smallest diameter class) function is also specified.

The simplest method for computing transition probabilities between size classes is to estimate the average proportion of trees that move between size classes as represented in the sample data (Usher 1966; Buongiorno and Michie 1980). An alternative method, which treats the estimation of the transition probabilities between size classes as a stochastic process, is to use a statistical technique known as the multinomial logit model (e.g., Boltz and Carter 2006; Macpherson et al. 2012). In this method, each measured tree is considered a unit of observation, and maximum likelihood methods are used to estimate the probability of a tree remaining within a class, moving into another class, or dying. This procedure smoothes the distribution of transition probabilities relative to the use of proportional estimates and allows for either deterministic (using the estimated mean) or stochastic (using the standard error of the mean) projections of future stand growth and yield. Recruitment can be estimated using a linear (e.g., Boltz and Carter 2006) or Poisson (Macpherson et al. 2012) regression model.

Using matrix notation, a general linear model of the growth of tropical forest stands can be represented as a system of linear difference equations either for one time period

$$n^{t+1} = An^t \quad (12)$$

or for several (k) time periods

$$n^{t+k} = A^k n^t \quad (13)$$

where n is a size abundance vector for the stand, whose elements are the numbers of trees in each size class, and A is an $m \times m$ matrix of transition rates between size classes, a_{ij} , $i, j = 1, \dots, m$. The dynamics embedded in Eqs. 12 and 13 depend upon the eigenvalues of A .⁵ For large t , the proportion of individuals in each stage become constant, similar to the stationary solution in the C-T bioeconomic model, and the asymptotic dynamics of the population are given by the value of the largest positive eigenvalue of A , λ_{\max} .

Matrix population models are built on the assumption that the transition probabilities are stable over time, so these models cannot account for the effects of different sites, stand structures, competitive

⁵Eigenvalues are the values λ that satisfy the equations $An = \lambda n$ for some vector n and are found by solving the characteristic equation $\det[A - \lambda I] = 0$ where $\det[\cdot]$ is the determinant (Usher 1966; Getz and Haight 1989; Vanclay 1995).

relationships, or abiotic factors such as changes in climate. As such, matrix models are best suited to projections over a limited number of cutting cycles. Further, it may be useful to estimate the sensitivity of forest stand projections to slight changes in transition probabilities, particularly if research is concerned with the persistence of specific tree species (Ehrlén and Groen­dael 1998; Caswell 2000).

Alternative timber harvesting strategies can be evaluated using matrix population models by removing different numbers of individuals from each diameter class and evaluating the impact on growth of the remaining stand. For example, letting h_i represent the proportion of diameter class i trees surviving the harvest (accounting for harvesting related mortality to trees in the residual stand), the matrix model shown in Eq. 11 can be modified as

$$n^{t+1} = HAn^t \quad (14)$$

where H is a diagonal matrix (h_1, \dots, h_m) and m is the number of diameter classes. The dominant eigenvalue λ_{\max} of HA provides an estimate of the growth rate of the harvested population. To obtain the harvest providing the maximum sustainable yield, λ_{\max} must equal 1 (Caswell 2001, p. 642; Getz and Haight 1989, p. 47).⁶

In addition to biological growth and yield functions, additional restrictions are used to specify logical constraints, such as limiting the harvest volume to be less than or equal to the volume available for harvest, and specific management concerns, such as limiting harvests to trees that exceed a given diameter limit or that leave a diverse mix of species in the residual forest.

Find the Optimal Solution

Once the objective function and constraint set have been specified, linear or nonlinear mathematical programming techniques are used to find an optimal solution (e.g., Getz and Haight 1989). When the problem consists of an objective function that is linear in the variables, and is subject to a set of linear constraints, the problem can be solved using the simplex method of linear programming (e.g., Chiang 1974). However, the objective function may be specified as a nonlinear function of economic variables (e.g., gross profit per unit may decrease as output increases), and the set of constraints may likewise be specified as nonlinear functions (e.g., competition may influence tree growth, mortality, and fecundity). In this case, nonlinear programming methods, based on the Kuhn-Tucker conditions, are required to find an optimal solution (e.g., Chiang 1974).

Applications of Discrete-Time Bioeconomic Model to Tropical Forests

The use of matrix population models for modeling tropical forest dynamics became popular in the mid-1990s (e.g., Alvarez-Buylla 1994; Alvarez-Buylla et al. 1996), and among the first papers to recognize the utility of this modeling approach for designing sustainable timber harvesting systems was the paper by Boot and Gullison (1995) (Table 2). In this paper, the authors described how matrix models can be used to identify the maximum sustainable yield of timber or non-timber products. Managers can then decide whether and how much to harvest based on the economic returns and impacts on the forest ecosystem of different harvesting intensities up to that maximum.

⁶Recognizing that timber harvesting can cause substantial damage to the residual stand, damage estimates can be specified as a function of harvest intensity (Macpherson et al. 2010; Indrajaya et al. 2014). In this case, the matrix model can be explicitly written $n^{t+1} = HDAn^t$, where D is a diagonal matrix (d_1, \dots, d_m) describing the percentage of trees killed in each diameter class for each tree harvested. Some damaged trees may die several years after harvest, and it may be challenging to include these trees in the specification of D .

Table 2 Discrete-time bioeconomic studies related to tropical forests

Authors	Subject	Objective function
Boot and Gullison (1995)	Timber harvest intensity	Income to loggers
Ingram and Buongiorno (1996)	Timber harvest intensity and biodiversity protection	Net present value to loggers
Boscolo and Buongiorno (1997)	Timber harvest intensity, biodiversity protection and carbon sequestration	Soil expectation value to landowners
Bach (1999)	Logging technology and timber damage	Net present value to loggers
Boscolo and Vincent (2000)	Logging technology, timber damage, carbon storage and stand diversity	Net present value to loggers
Namaalwa et al. (2007))	Optimal forest/agricultural land use	Net present value to loggers
Macpherson et al. (2012)	Logging technology and timber damage	Net present value to loggers

Shortly after the Boot and Gullison (1995) study, Ingram and Buongiorno (1996) showed how linear programming, in combination with matrix population models, could be used to find optimal harvesting regimes for tropical forests. Using the Shannon-Weiner index to measure diversity of lowland tropical forest in Peninsular Malaysia, the authors concluded that focusing harvests on 30–40 cm dipterocarp and non-dipterocarp species every 10 years would maintain trees in every species and size class while providing economic returns that were similar to the highest yield under current management regimes.

A damage matrix representing the effects of logging on the residual stand was added to a transition matrix of tropical forest growth and used to evaluate trade-offs between timber, carbon storage, and tree diversity in Peninsular Malaysia (Boscolo and Buongiorno 1997). The results of this study indicated that the goals of increasing carbon storage and tree diversity can only be met by sacrificing substantial amounts of income.

Bach (1999) also incorporates damage to the residual stand into his model of four species groups in Ghana. He examines how profit-maximizing concession holders would respond to higher timber prices and to area subsidies for reduced-impact logging (RIL) practices. The objective function is net present value to the concession holder from timber harvest over 100 years, assuming the average 10,000 HA concessions and the legally required 40 years cutting cycle in Ghana. It was found that subsidizing the costs associated with RIL is far more efficient than subsidizing the prices of tropical timber (Bach 1999).

Boscolo and Vincent (2000) adapt the model from Boscolo and Buongiorno (1997) to examine loggers' choice of harvest technology and level (i.e., number of trees by species group and size class). In this model, adopting RIL techniques increases the fixed cost of logging but reduces damage to the residual stand, and loggers maximize the net present value of profits from harvest over a time horizon determined by the length and possibility of renewing their concessions. The authors concluded that loggers may be induced to adopt RIL systems through the imposition of relatively small performance bonds, but that relatively large performance bonds would be needed to get loggers to obey restrictions on minimum diameter cutting limits.

Namaalwa et al. (2007) model harvest of wood fuel and clearing of forests by villages in Uganda, assuming that they maximize the net present value of cash flows over a 20 year time horizon. Their model embeds a standard matrix model that determines the tree stock as a result of diameter increment, recruitment, mortality, and harvesting. Based on their model, they conclude that it is very difficult to design and implement policies that maintain forest biomass density.

Macpherson et al. (2012) develop a matrix model with five species groups and information on the costs and damages of logging based on data from Paragominas in the eastern Brazilian Amazon. They examine steady-state solutions that maintain the standing volume of merchantable timber, as well as modeling how loggers and consequently forests respond to current regulations. They find that loggers can profit from

adopting RIL techniques, primarily because of the reduced operational costs rather than the increased revenues from future harvests. They conclude that future harvests will still be profitable, although the structure and composition of the forests will be different and profits will be lower than at first harvest.

Conclusions and Emerging Research Directions

Although the number of applications of bioeconomic analysis to tropical forest management is limited, this modeling approach has yielded several insights that are critical to understanding tropical forest sustainability. First, bioeconomic models clearly demonstrate the importance of the rate of time preference used to discount future values to the present in determining optimal forest stocks. In particular, discount rates that exceed the rate of tropical forest growth help to explain deforestation and conversion of forests to other land uses. Second, although it is widely recognized that non-timber ecosystem services provide substantial social value, the lack of empirical estimates of the nonmarket values provided by tropical forests constrains the ability of decision-makers to meaningfully evaluate trade-offs. However, C-T bioeconomic models that include a qualitative measure for ecosystem service values indicate the importance of including this component in quantitative economic analyses seeking to address the appropriate balance between timber and non-timber services provided by tropical forests. Third, while individual D-T bioeconomic analyses have limited generality due to their reliance on site-specific data, the overall set of models that have been implemented indicate the relative magnitude of public subsidies or costs of other policy innovations that would be required to induce loggers to modify their behavior and adopt sustainable harvesting practices.

The conceptual models described in this chapter have been intentionally simplified in hopes of developing intuition regarding their application to problems in tropical forest management. However, both C-T and D-T bioeconomic models are very general and can be applied to a suite of emerging and challenging problems. We suggest that future bioeconomic analysis of working forests in the tropics may help inform decision-making regarding sustainable forest management by investigating the following topics:

- Bioeconomic models of tropical forests have generally ignored complex ecosystem dynamics. While making bioeconomic analysis more tractable, simple models of tropical forest growth overlook potentially critical factors such as specific interactions among multiple species and the possibility of crossing ecological tipping points (e.g., Barlow and Peres 2008; Malhi et al. 2009; Nobre and Borma 2009). However, bioeconomic analysis has already shown that nonlinearities existing between the growth of non-harvested and harvested forest species can induce multiple steady states in boreal forests (Crépin 2004), making the choice of an optimal path much more complex. Bioeconomic models have also demonstrated that nonlinear and non-convex feedbacks between economic control variables and ecosystem dynamics can cause massive ecosystem regime changes (Crépin et al. 2011). By incorporating complex feedback between economic and ecological variables, bioeconomic analysis can help decision-makers understand the long-run opportunities and vulnerabilities provided by alternative forest management strategies.
- Although a substantial amount of research in developed countries has focused on the production and value of ecosystem services provided by forests, little is known about the production of nonmarket economic values from tropical forests. Bioeconomic analysis linking the production and valuation of

tropical forest ecosystems for timber and non-timber services could help decision-makers better understand the trade-offs between a suite of ecosystem goods and services.

- Economists have begun to appreciate that a case for intergenerational equity in centuries-scale problems, such as climate change and the protection of biological diversity, can be made by the use of discount rates that decline asymptotically toward zero over time (Carson and Tran 2009). However, policy-makers, forest dwellers, private entrepreneurs, and other groups may all hold dramatically different rates of time preference regarding the use of tropical forests. Because many policy issues regarding tropical forests are long-lived and affect many generations into the future, a better empirical understanding of the rates of time preference held by people who benefit from tropical forests would help calibrate bioeconomic models to actual conditions.
- Bioeconomic models of tropical forest use have generally ignored the issue of uncertainty. Where ambiguity exists regarding the nature of a correct model, one approach is to use robust controls that perturb a benchmark model so that alternative futures can be evaluated (Vardas and Xepapadeas 2010). This approach, as applied to biodiversity management, appears to offer a fruitful area for bioeconomic research that is directly applicable to emerging issues in tropical forest management during the twenty-first century.
- Finally, bioeconomic models of tropical forest management have barely begun to consider political-economic dynamics (e.g., Kant 2000). A fuller consideration of governance, institutions, and other socioeconomic factors may help bioeconomic models provide more realistic analyses of factors influencing tropical forest sustainability.

Appendix

Simulation of the Optimal Stocking of a Tropical Timber Production Forest Using the Continuous-Time Bioeconomic Model

In this Appendix, we illustrate how the analysis presented in section “[Continuous-Time Bioeconomic Models of Tropical Forests](#)” can be used to determine the optimal stocking of a tropical timber production forest. In order to make the example tractable for empirical analysis, we first need to make some general assumptions about the functional form of the social welfare function and the forest growth function. For our empirical example, we follow the renewable resource model described in Chichilnisky et al. (1995, p. 178). Second, we also need to make some assumptions about the ecosystem service benefits provided by a standing tropical forest. For expository purposes, we use information on household willingness to pay for tropical forest conservation among upper-middle income tropical countries (Vincent et al. 2014).

A common assumption used in economic analysis is that the social welfare function is additive in its arguments and that welfare increases at a decreasing rate. These assumptions are easily incorporated into our analysis by revising Eq. 1 to read

$$\max W = \int_0^{\infty} [\ln C_t(h_t) + Y \ln B_t(x_t)] e^{-\delta t} dt \quad (15)$$

where “ln” refers to the natural logarithm of the associated argument. This functional form assures the property of diminishing marginal utility. Further, in Eq. 15, γ is a parameter describing the relative value of ecosystem service benefits received from the standing forest (B) relative to the consumption value (price) of harvested timber (C). The value of this parameter is derived below.

Next, we rewrite Eq. 2 by specifying a (assumed) logistic growth function for timber stocks, post-harvest:

$$\dot{x} = G(x) = rx_t - \frac{rx_t^2}{K} \quad (16)$$

where r is the intrinsic growth rate, x is the timber stocking level, and K is the carrying capacity of the tropical forest.

Substituting these equations into the Hamiltonian (Eq. 3), taking the first-order conditions (Eqs. 4 and 5), and simplifying, we find that the optimal “utilitarian” steady-state condition for timber stocks (x^u) is

$$x^u = \frac{K(\gamma r - \delta + r)}{2r + \gamma r} \quad (17)$$

Thus, if no economic value is assigned to the ecosystem service benefits associated with a standing forest ($\gamma = 0$), and if the opportunity cost of capital is zero ($\delta = 0$), then the optimal stocking is simply $K/2$, which is the stocking level corresponding to the maximum sustainable yield (MSY).

By setting $\delta = 0$, allowing the ecosystem service benefits to have a positive economic value ($\gamma > 0$), and simplifying, Eq. 17 yields the Green Golden Rule for tropical timber (x^{GGR}):

$$x^{GGR} = K \frac{(\gamma + 1)}{(\gamma + 2)} \quad (18)$$

(Chichilnisky et al. 1995).

Tropical forest growth parameters for our example are derived from a timber harvesting experiment conducted in the Tapajós National Forest located in the Brazilian Amazon (Silva et al. 1995). The authors of that study note that, as is typical of upland forest types in this region, the carrying capacity (K) for all tree species exceeding 45 cm diameter at breast height, is up to $200 \text{ m}^3 \text{ ha}^{-1}$. Assuming that timber growth in this forest follows the logistic growth function described above, we estimate MSY (for all tree species) as $K/2 = 100 \text{ m}^3 \text{ ha}^{-1}$. Although current Brazilian forest law restricts harvests to not exceed $25 \text{ m}^3 \text{ ha}^{-1}$ (and the cutting cycle to not be less than 30–35 years), the harvesting intensity in this experiment removed about $75 \text{ m}^3 \text{ ha}^{-1}$. During the 11 year post-harvest period examined in the experiment, the relative (%) increment of commercial timber volume averaged about 3 % annually – which was very similar to the relative (%) annual increment of all timber species (Table 6, p. 273). Roughly 50 of the timber species recorded in this experiment are currently accepted by the market. While this does not include all tree species growing in this forest, we assume that all timber species are available for commercial harvest in order to simplify this example. Thus, the annual volume growth rate (0.03) on the post-harvest stocking level ($125 \text{ m}^3 \text{ ha}^{-1}$) is roughly $4 \text{ m}^3 \text{ ha}^{-1}$. Setting $\dot{x} = 4$ in Eq. 16, and solving for r , we find that the intrinsic rate of growth (r) of trees in this forest is 0.085. This provides us with the second of three parameters required to solve Eq. 17.

The third key parameter needed in Eq. 17 is the marginal economic value of ecosystem service benefits provided by standing tropical forests (γ). Although the determination of this value would, in most cases, require an economic study specifically designed for the forest region under investigation, for the sake of illustration, we use estimates of household willingness to pay for tropical forest conservation in Malaysia (Vincent et al. 2014). In that study, the authors found that the household willingness to pay for tropical forest conservation in a specific tropical forest of 100,000 ha was US\$1.08 per month. As the Tapajós

National Forest is roughly 500,000 ha, we multiply this amount by 5, for a monthly WTP amount and then by 12 to obtain an annual WTP amount for tropical forest conservation. Using the standard capitalization formula to translate the annual WTP for tropical forest conservation into the asset value of the standing forest stock, we find that the asset value (using 4 % for the social discount rate for tropical forest stocks), per household, is roughly \$1,620 ha⁻¹ for standing forest stocks in the Tapajós National Forest. The WTP per hectare and per cubic meter, per household, can be found by dividing through by the number of hectares (500,000) and cubic meters per hectare (200). Multiplying this amount (\$0.0000162 per m³) by the current estimated number of households in the state of Pará (2.7 million) yields a total WTP estimate of \$43.20 per cubic meter of standing forest. A recent study of (net) commercial value of timber in the Tapajós National Forest of about \$20 per cubic meter (Humphries et al. 2012) suggests that the relative price benefit (γ) of standing timber to harvested timber is roughly 2.16 under the assumptions made here.

Given these assumptions, we can now determine the optimal tropical timber stocking associated with the utilitarian solution (for different discount rates) and the Green Golden Rule (where the discount rate equals zero). This is accomplished by placing Eqs. 17 and 18 in a spreadsheet and solving for the optimal stocking level given:

$$K = 200 \text{ m}^3$$

$$\gamma = 2.16$$

δ = an assumed discount rate, ranging between 0.01 and 0.05 for the utilitarian solution

In the case of the utilitarian solution, the optimal stocking levels will be: 136 m³ ha⁻¹, 120 m³ ha⁻¹, 103 m³ ha⁻¹, 87 m³ ha⁻¹, and 72 m³ ha⁻¹ for social discount rates of 0.01, 0.02, 0.03, 0.04, and 0.05. In the case of the Green Golden Rule, when the social discount rate equals zero, the optimal stocking level will be 152 m³ ha⁻¹. As anticipated, this level exceeds the optimal stocking level when discount rates are positive, as well as the optimal stocking level associated with the MSY.

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