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ECONOMICS OF AGROFORESTRY

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Abstract

This chapter provides principles, literature and a case study about the economics of agroforestry. We examine necessary conditions for achieving efficiency in agroforestry system design and economic analysis tools for assessing efficiency and adoptability of agroforestry. The tools presented here (capital budgeting, linear programming, production frontier analysis and risk analysis) can help determine when agroforestry is a feasible option and provide arguments for cases when agroforestry systems are economically, socially and environmentally appropriate, fostering improved sustainable development for landowners, farmers and communities. The chapter closes with a case study applying the capital budgeting and real options analysis to evaluate the potential for agroforestry to augment efforts to restore bottomland hardwood forests in the Lower Mississippi Alluvial Valley. Agroforestry systems provide multiple outputs, potentially reducing risk and increasing income while also purportedly producing more ecosystem services than conventional agriculture. Our review and case study, however, provide cautionary tales about the limits of agroforestry and the need for rigorous economic research and analysis to design efficient and productive agroforestry systems and to optimize private and public investments in agroforestry.

Keywords

Capital budgeting, linear programming, real options, silvopasture, production frontier, agroforestry

Introduction

Agroforestry is 'a land-use system that involves deliberate retention, introduction, or mixture of trees or other woody perennials in crop or animal production systems to take advantage of economic or ecological interactions among the components' (SAF, 2012). Examples include: intermixed crops and trees on small farms (most often in developing countries), where the trees provide shade, fuel or fodder; silvopasture (mixed grazing and trees); shade-grown coffee or cocoa; and windbreaks, shelterbelts and riparian buffers. Potential advantages include reducing financial and biophysical risks, improving crop yields or quality, reducing fertilizer or other chemical inputs, improving livestock health, adapting to climate change through more resilient production systems, retaining more land at least partially forested, reducing soil erosion and increasing biodiversity.

Small-scale agroforestry, common in the tropics, provides multiple products for small farmers and good mixes of low-cost inputs. Medium-scale agroforestry may involve larger crop systems and focus on two or three simple tree and crop or grazing systems. Large-scale agroforestry remains uncommon, with silvopasture perhaps the most promising (Cubbage et al., 2012). No matter how efficient and eco-friendly they are, agroforestry systems can contribute to sustainable land use only if they are adopted and maintained over long time periods (Mercer, 2004). Adoption of agroforestry is considerably more complex than most agricultural innovations, because it usually requires establishing new input-output mixes of annuals, perennials and other components, combined with new conservation techniques such as contour hedgerows, alley cropping and enriched fallows (Rafiq, Amacher and Hyde, 2000). The multicomponent, multiproduct nature of agroforestry may limit adoption due to the complex management requirements and long periods of testing, experimenting and modification. For example, most agroforestry systems take 3 to 6 years before benefits begin to be fully realized compared to the few months needed to evaluate a new annual crop (Franzel and Scherr, 2002). The additional uncertainties in adopting new agroforestry input-output mixes suggests that agroforestry projects will require longer time periods to become self-sustaining and self-diffusing than earlier Green Revolution innovations.

Efficiency in agroforestry design

The efficiency objective of agroforestry is to optimize the use of all available resources to enhance the sustainable economic development of farms and communities. Meeting the efficiency objective requires the social marginal benefits from agroforestry (e.g. increased wood and food production, reduced soil erosion, carbon sequestration, etc.) to exceed the social marginal costs (e.g. production inputs, externalities). The net benefits from agroforestry must also equal or exceed the net benefits from identical investments in alternative land uses. Given efficient local markets, sustainable self-initiated agroforestry systems meet these requirements or they would not continue to exist. However, nonmarket (external) benefits and costs of land use are often ignored in private land-use decision making. Therefore, projects and policies initiated by governments or donor agencies require more formal efficiency analysis and explicit consideration of positive and negative externalities with alternative land-use scenarios.

The production possibility frontier (PPF) shows efficient combinations of the annual and woody perennial crops that can be produced with a given level of inputs. Agroforestry systems typically exhibit a composite of three possible production relationships (Figure 13.1). In the extreme areas (*ab* and *de*), combinations of trees and annual crops are *complementary*. This could occur when adding trees to agriculture reduces weeding, increases available nitrogen, improves microclimate or reduces erosion control costs (as in area *ab*). At the other extreme (area *de*), intercropping annual crops during tree plantation establishment may also reduce weeding costs and increase tree production. However, as either more trees are added to crop production or more crops to tree production, competition for nutrients and light dominate to produce the *competitive* region *bd*. *Supplementary* relationships occur at points *b* and *d*.

Data on the value of the outputs, usually the market price, are used to construct the iso-revenue line in Figure 13.1. The slope of the iso-revenue line is the rate at which the two goods can be exchanged (i.e. market prices). The landowner's goal is to reach the highest possible

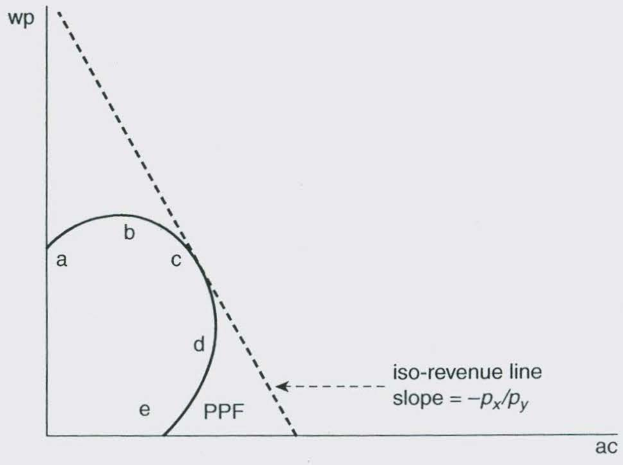

Figure 13.1 Concave production possibility frontier (PPF) resulting in agroforestry as optimal choice wp = woody perennial output, ac = annual crop output, c = optimal combination of wp and ac (Mercer and Hyde, 1992).

iso-revenue line, where income is maximized; this occurs at the tangency of the iso-revenue line and the PPF, point *c* in Figure 13.1. A PPF concave to the origin is a necessary condition for agroforestry to be feasible. Specialization can also be optimal with a concave PPF when the iso-revenue line is either very flat or steep, i.e. when one product is much more highly valued than the other. With convex PPFs, the optimal solution is to specialize in annual crops or forestry, depending on the price ratio, but not agroforestry. This occurs when the trees and crops are strictly competitive or when economies of scale favor monocultures over mixed tree and crop regimes.

Payments for ecosystem services (carbon sequestration, soil erosion control, water quality, biodiversity) will often be crucial for the widespread adoption of agroforestry systems (Frey, Mercer, Cubbage and Abt, 2010). Optimal production decisions from the landowner's perspective are determined by the PPF and the relative private value (e.g. market prices) of all alternatives. From society's viewpoint, however, market prices rarely reflect the social value of the ecosystem services associated with alternate land uses. For example, nonmarket benefits (e.g. erosion control and water quality protection) provided by the trees may increase their value to society. Likewise, negative externalities associated with the annual crops may reduce their social value. Therefore, when determining optimal production for society, the values (shadow prices) of the outputs should be adjusted to include external costs and benefits.

Figure 13.2 illustrates how optimal production decisions can vary between landowners and society. The private iso-revenue line reflects the landowner's relative valuation of the outputs based on their market prices, p_x and p_y; the social iso-value line reflects the social value of all outputs based on their shadow prices, sp_x and sp_y. Here, society values woody perennial production more than is reflected in the market price because of the positive externalities associated with trees. As a result, $sp_y > p_y$ and the slope of the social iso-value line is lower than the private iso-revenue line ($-sp_x/sp_y < -p_x/p_y$). Optimal production from the landowner's perspective occurs at *A*, specialization in annual crop production. From society's viewpoint, however, optimal production occurs at point *B*, an agroforestry combination. Therefore, it may benefit society to provide incentives to encourage adoption of agroforestry to move closer to point *B*.

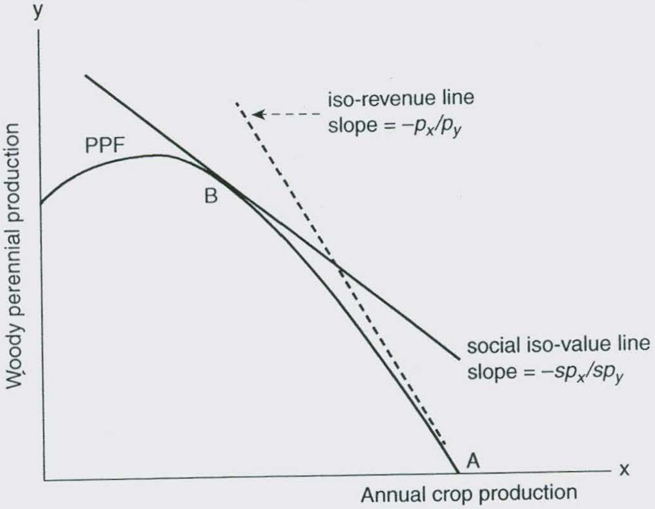

Figure 13.2 Social versus private optimal production decisions (p_x and p_y = market prices of x and y, sp_x and sp_y = shadow prices of x and y; Mercer and Hyde, 1992).

Economic approaches for assessing agroforestry

Capital budgeting

Capital budgeting (cash flow or cost-benefit analysis) is a simple, powerful tool for comparing the efficiency (profitability) of alternative land uses (Klemperer, 1996). Although the previous description of production possibilities is useful for identifying the optimal combinations of inputs and outputs within a continuum of land uses, capital budgeting allows comparisons of alternatives that utilize different inputs and produce different outputs. The most common capital budgeting tool is Net Present Value (NPV), the sum of the discounted periodic net revenues per unit of land over a given time horizon. If the NPV is higher for agroforestry than for all feasible alternatives, it is potentially adoptable. The Soil Expectation Value (SEV) is more appropriate when the time horizons of alternatives vary. SEV calculates the net return per hectare assuming the regime will be repeated in perpetuity. Frey et al. (2010) showed how SEV can be altered for regimes that do not involve fixed rotations. Multiplying SEV by the interest rate, *r*, gives the Annual Equivalent Value (AEV). AEV is useful when comparing forestry and agroforestry to systems such as agriculture, where yearly returns are the norm.

NPV, SEV and AEV are appropriate when land is the most limiting factor of production. In many common agroforestry situations, however, capital, labor or time will be the most limiting factor (Franzel, 2004). Table 13.1 provides a scenario for each production input and relevant capital budgeting criteria that maximizes returns to the most limited factor. The Benefit-Cost Ratio (BCR) compares discounted benefits to costs as a unitless proportion rather than a difference as in NPV. Potential benefits and costs can be expressed per unit of land or as a total for the project because the units cancel. Internal Rate of Return (IRR) is the discount rate that makes the NPV equal zero. It is often used in practice, even though it is not as theoretically appropriate as NPV for most producers with limited land and relatively high levels of access to capital. IRR has intuitive appeal and is appropriate when a producer does not have a set discount rate.

Table 13.1 Limiting factors of production, potential scenarios and appropriate capital budgeting criteria.

Limiting factor	*Scenario*	*Capital budgeting criteria*
Land	• Landowner with access to credit and labor • High transaction costs for acquiring land • Larger family forest landowner in developed country	NPV, SEV, AEV
Capital	• Fixed level of investment capital • No constraints to land acquisition • Timber Investment Management Organization • Limited-resource farmer with sufficient land and family labor but no/limited access to credit	BCR, IRR
Labor	• Limited-resource or small family farmer with sufficient land but thin or nonexistent labor markets	DRW
Time	• Limited-resource farmer with access to capital at high interest rates and/or needs for quick returns for subsistence	Payback period, IRR

Conceptually, constraints to time are similar to constraints to capital (both indicate a high discount rate), so IRR is often a good criteria for both. Discounted Returns per Workday (DRW), the ratio of the discounted net revenues to discounted wages, expressed in dollars per workday, can be used when labor is the limiting asset.

Linear programming

When the objective is maximizing long-term profits from the entire farm under multiple constraints, linear programming (LP) is often the tool of choice. LP models differ from capital budgeting in two important ways. LP models the entire farm, not just the activity of interest, and accounts for diversity among farms. Each farm is modeled separately and aggregated to evaluate potential adoptability in a particular region. Mudhara and Hildebrand (2004) use LP to assess the impact of adopting improved fallows on household welfare and discretionary income in Zimbabwe. Thangata and Hildebrand (2012) used ethnographic linear programming (ELP) to examine the potential for agroforestry to reduce carbon emissions in sub-Saharan Africa. ELP provides insights into the complexity and diversity of smallholder farm systems by accounting for three important aspects in agroforestry decision making: (1) farmers' resource endowments (land, labor, capital), (2) farmers' multiple objectives (profits, subsistence needs, education, etc.) and (3) market conditions (prices, access, etc.). Dhakal, Bigsby and Cullen (2012) used LP to model the effects of government forest policies on households using community forests in Nepal. Their model captures the economic impacts of forest policy changes on landowners and the supply of forest products from private and community forests.

Production frontier analysis

Figure 13.3 depicts a production frontier, the maximum output that can be produced for any given level of input. Points *a*, *b* and *c* represent three farms or 'decision-making units' (DMUs).

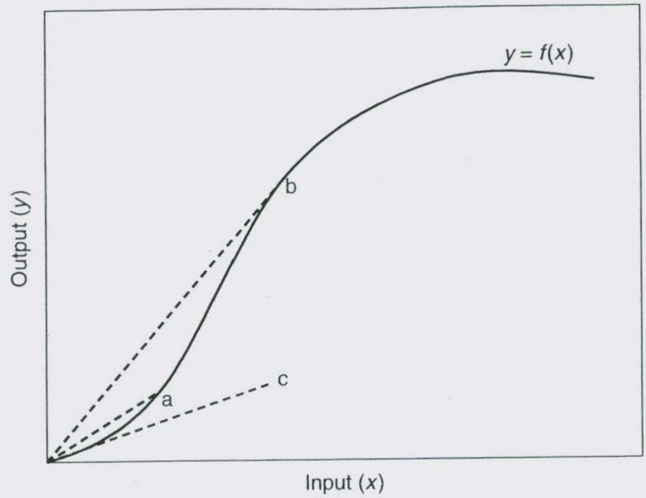

Figure 13.3 Production frontier: Slope of dashed lines represents technical efficiency of decision-making units *a*, *b* and *c*.

Total technical efficiency (TE)[1] is measured as the slope of the line segment from the origin to that DMU's point on the production frontier. In Figure 13.3, DMU *b* has the highest TE, *a* the middle and *c* the lowest. TE can be decomposed into two components: scale efficiency and pure TE. Both DMU *a* and *b* are operating at 100% pure TE because they lie on the production frontier. However, DMU *a* has a lower scale efficiency than DMU *b* because it could increase its total TE by expanding. DMU *c*, on the other hand, has lower pure TE than both *a* and *b* because it produces the same output with more inputs than *a* and less output with the same level of inputs as *b*.

In one input/one output cases, calculating TE is simple. The most efficient DMU produces the maximum output per unit of input (the slope of the line through the origin to the DMU's point). With multiple inputs and outputs, however, measuring relative efficiency becomes more complicated. One possible measure is the ratio of the weighted inputs to weighted outputs. If all outputs and inputs have market values, the prices are the weights and TE is equivalent to the benefit-cost ratio. However, in many situations (particularly in the developing world), markets are thin, prices may not exist and/or farmers may lack access to markets. In this case, benefit-cost ratios are not comparable between farms, but two methods (parametric and nonparametric) are available that account for the curvature of the production frontier (Bravo-Ureta and Pinheiro, 1993).

Parametric methods assume a specific functional form (e.g. Cobb-Douglas) and typically use corrected ordinary least squares or maximum likelihood to estimate parameter coefficients. Bright (2004) provided examples of production possibilities frontiers for agroforestry systems and multiple monocultures within a single farm. Lindara, Johnsen and Gunatilake (2006) applied stochastic frontier analysis using a Cobb-Douglas production function to evaluate factors affecting the TE of spice-based agroforestry systems in Sri Lanka.

Data envelopment analysis (DEA) uses LP to determine the weights that maximize TE without specifying a functional form and assuming that no DMU or linear combinations of the DMUs are 100% efficient. DEA is suited for comparing the efficiency of DMUs faced with multiple inputs and outputs, some of which may have no market value, a common situation in developing regions. Essentially, DEA picks weights (relative shadow prices) for each input and output to maximize TE.

Allowing the weights to vary is useful in at least three ways. First, using weights rather than market prices is critical when markets are thin or nonexistent. Second, prices for inputs or outputs often vary between regions, so that choosing a price from a single region or using a mean price can affect the efficiency measure. Third, individual farmers may value inputs or outputs differently than the market price due to government subsidies, individual preferences, subsistence and so forth. DEA can reduce the effects of the resulting distortions.

Figure 13.4 displays DMU_0 as a linear combination of the other DMUs. If any linear combination produces at least as much of each output and uses less input than DMU_0, then DMU_0 is inefficient. In other words, efficient farms and linear combinations of efficient farms form an envelope, which represents the production frontier. Inefficient levels are calculated as the relative distance from the efficient envelope. In Figure 13.4, DMUs *a* and *b,* located on the empirical efficient frontier (the 'envelope'), are 100% efficient. DMU *c* produces the same output using more inputs than a linear combination of *a* and *b*, located at point *x*, and thus, *c* is inefficient.

Frey et al. (2012) applied DEA to compare the relative efficiency among silvopasture, conventional pasture and plantation forestry in Argentina. Then, they applied nonparametric statistical analysis to compare the systems within farms. Silvopasture was found to be more efficient than conventional cattle ranching, but results were inconclusive for conventional forestry. Pascual (2005) utilized both parametric (stochastic production function analysis) and nonparametric data envelope analysis to examine the potential for reducing deforestation by improving the efficiency of traditional slash-and-burn milpa systems in Mexico. They found that deforestation would be reduced by 24% if households operated on the production frontier.

Risk and uncertainty

The expected utility paradigm is the theoretical foundation for most analyses of investment under uncertainty (Hildebrandt and Knoke, 2011). Rather than analyzing risk and return separately, expected utility theory examines the entire distribution of returns simultaneously. The

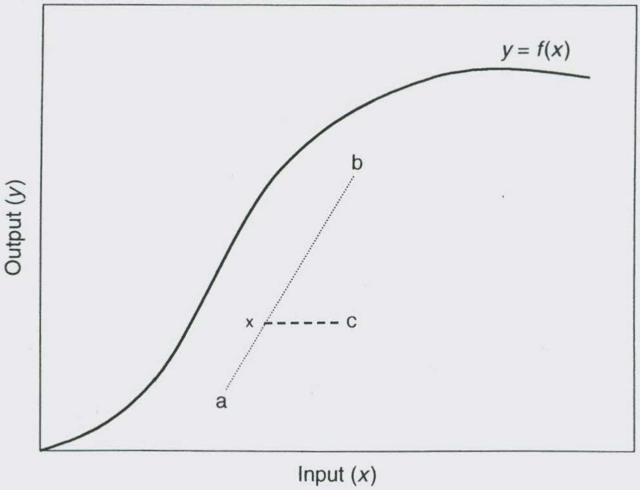

Figure 13.4 Envelope formulation: Decision Making Unit *c* is inefficient relative to *a* and *b* because *x*, a linear combination of *a* and *b*, produces the same output as *c* with fewer inputs.

decision maker chooses between uncertain prospects by comparing their expected utility values, i.e. the weighted sums obtained by adding the utility values of outcomes multiplied by their respective probabilities.

Mean variance analysis

The objective of risk research based on Markowitz's (1959) mean-variance hypothesis is to find the subset of 'efficient' portfolios that minimize risk for any given level of returns or, conversely, maximize returns for any given level of risk. Mean-variance (usually denoted E-V for 'expected value/variance') analysis can be very powerful, but the underlying assumptions limit it to a fairly restricted set of situations. E-V assumes that either the agent has a quadratic utility function, assets have normally distributed returns or both (Feldstein, 1969). These assumptions can cause large deviations from expected utility maximization, depending on the form of the utility function. Nevertheless, E-V is quite robust in approximating efficient expected utility maximization under a wide variety of utility functions and common levels of risk-aversion (Kroll, Levy and Markowitz, 1984).

E-V is often evaluated using quadratic programming (Steinbach, 2001) in which variance for given levels of expected returns is minimized by allowing the investments in each asset to vary. Repeating the quadratic program for a range of expected returns produces the frontier of efficient portfolios. Lilieholm and Reeves (1991) and Babu and Rajasekaran (1991) used E-V to analyze the efficient allocation of agroforestry within the whole farm and showed that adopting agroforestry can be optimal for certain levels of risk aversion. Ramirez et al. (2001) compared the financial returns, stability and risk of six cacao-laurel-plantain systems, and Ramirez and Sosa (2000) assessed the financial risk and return tradeoffs for coffee agroforestry systems in Costa Rica. Both studies evaluated expected returns and financial risk based on E-V analyses of estimated cumulative distribution functions of the NPVs and demonstrated the need to allow for the possibility of nonnormality of the variables in NPV analyses.

Stochastic dominance

Stochastic dominance (SD) encompasses the entire probability distribution of outcomes, does not require normality for the utility functions and requires only minimal assumptions about preferences (Hadar and Russell, 1969). Due to less restrictive assumptions and use of partial information, SD results are less deterministic and typically only provide a partial ranking of efficient and inefficient alternatives. Therefore, SD is commonly used for initial screenings of alternatives to provide a partial ordering based on partial information (Hildebrandt and Knoke, 2011). Castro, Calvas, Hildebrandt and Knoke (2013) applied SD to analyze the uncertainties associated with using conservation payments (CP) to preserve shade coffee in Ecuador. They investigated the effects of land-use diversification on CP by allowing different combinations of coffee agroforestry and monoculture maize production on farms. CP were two to three times higher when calculated with SD compared to maximizing a concave utility function, and Castro et al. concluded that the assumptions underlying SD are inappropriate for risk-averse farmers.

Real options

Land-use practices vary widely in their flexibility, and the best land managers include the value of the option to change or postpone actions in their decision calculus. Although deterministic models can incorporate changing future conditions and optimize decisions that adapt to these circumstances, they are inappropriate under risky or uncertain conditions because they assume perfect foresight. Stochastic analyses using real options (RO) techniques can estimate the value of flexibility given uncertain future conditions. The key difference between RO and capital budgeting is the recursive nature of the RO decision-making process. RO assumes that decisions made in the current year can be put off until the future. For example, a land manager can put off timber harvest and reforestation decisions, based on current conditions. Utilizing both stochastic and deterministic models can provide important insights about financial decisions (Frey, Mercer, Cubbage and Abt, 2013).

RO analyses are based on the Bellman equation, which assumes that a decision maker chooses a management regime to maximize the sum of current and discounted expected future rewards (profit, utility, etc.):

$$
\begin{aligned}
&V_t(s) = \max_{x \in X(s)} \left\{ f(s,x) + \delta \cdot E_\varepsilon \left[V_{t+1}\left(g(s,x,\varepsilon) \right) \right] \right\}, \\
&s \in S, \\
&t = 1, 2, \ldots, T \qquad (1)
\end{aligned}
$$

$V_t(s)$ denotes the total land value at time t in state s, $f(s,x)$ are the gains from choosing x under state s, $\delta = 1/(1 + \rho)$ is the discount factor, ρ is the discount rate and $E[\cdot]$ is the expectation operator. T is the time horizon, and $g(\cdot)$ is the transition function from states s, actions x and shocks ε (variability, risk).

Most forest harvesting RO models have used Markov-chain, Monte-Carlo techniques to solve the Bellman equation. Recently, however, partial differential methods are usually preferred due to improved precision (Miranda and Fackler, 2002). In a partial differential, infinite-horizon model, all points in time become equivalent and the Bellman equation simplifies to:

$$
V(s) = \max_{x \in X} \left\{ f(s,x) + \delta \cdot E_\varepsilon \left[V\left(g(s,x,\varepsilon) \right) \right] \right\} \qquad (2)
$$

Partial differential collocation methods are used to solve equation (2) and determine the optimal regime for each state, $x(s)$.

Behan, McQuinn and Roche (2006) used RO to show that it is optimal for Irish farmers to wait longer to reforest or afforest than suggested by standard discounted cash-flow analyses because of establishment costs and the relative irreversibility of switching to forestry. Rahim, van Ierland and Wesseler (2007) used RO to analyze economic incentives to abandon or expand gum agroforestry in Sudan. They found that a 315% increase in gum Arabic prices would be needed to induce a shift in land use from agricultural production to gum agroforestry. Mithofer and Waibel (2003) used RO to analyze investment decisions for tree planting in Zimbabwe. They found that indigenous fruit tree planting is affected by tree growth rates and costs of collecting fruits from communal forests. Isik and Yang (2004) applied RO to examine participation in the Conservation Reserve Program (CRP) in Illinois. Although option values, land attributes and farmer characteristics significantly influenced participation, uncertainties in crop prices and program payments and irreversibilities associated with fixed contract periods were also crucial.

Next, we provide a case study (from Frey et al., 2010, 2013) applying capital budgeting and RO analysis to examine the potential for agroforestry to solve land-use problems in the Lower Mississippi Alluvial Valley (LMAV).

Case study: Agroforestry potential in the LMAV

The LMAV, the floodplain of the Mississippi River below the Ohio River (Figure 13.5), once contained the largest contiguous area of bottomland hardwood forest (BLH) in the United States. Beginning in the 1800s, converting BLH to agriculture has had a long history in the LMAV. For example, between 1950 and 1976, approximately one-third of the LMAV's bottomland forests were converted. Now, only a quarter of the original BLH survives, and what remains is degraded by fragmentation, altered hydrology, sedimentation, water pollution, invasive exotic plants and timber harvesting (Twedt and Loesch, 1999).

BLH forests provide critical ecosystem services, including wildlife habitat, clean water, flood mitigation and groundwater recharge, biogeochemical processes such as nutrient uptake and sediment deposition and carbon sequestration (Walbridge, 1993). However, the existing forest base has been reduced to the point where it can no longer meet society's demand for these services (Dosskey, Bentrup and Schoeneberger, 2012).

Beginning in the 1970s, a number of initiatives were introduced promoting BLH restoration in the LMAV; foremost are the CRP and the Wetlands Reserve Program (WRP). Although a significant amount of reforestation has occurred, most BLH remain characterized by continued deforestation and degradation. Agroforestry has been suggested as a means to augment BLH restoration by restoring trees on agricultural lands and producing at least some of the ecosystem services of natural BLH such as wildlife habitat and improved water quality (Dosskey et al., 2012).

In this case study, we illustrate the use of capital budgeting and RO to evaluate the potential adoptability of agroforestry in the LMAV. First, we use capital budgeting to compare profitability of agroforestry, production forestry and annual cropping with and without government incentives. Then, we apply RO analysis to examine how risk, uncertainty and flexibility affect the adoption decision.

Methods

Capital budgeting

Although agricultural and forestry management activities can take place year-round, we approximated them with discrete, yearly costs and benefits, as is common with forestry financial estimations. SEVs were used to compare expected returns from alternative investments in the LMAV (Klemperer, 1996). First, we calculated the NPV of the inputs required to produce a mature forest stand. Then, for even-aged management regimes, we estimated the financial returns from a clearcut, repeated in perpetuity to find SEV using:

$$SEV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \left[1 + \frac{1}{(1+r)^T - 1} \right] \tag{3}$$

where B_t and C_t are benefits (e.g. revenues from timber harvest or hunting lease) and costs (e.g. site preparation and maintenance) per hectare accrued in year t, T is the total number of time periods and r is the annual discount rate.

For uneven-aged regimes, we approximated the periodic sustainable harvest as a yearly harvest exactly equal to the mean annual increment and calculated the SEV for the annual sustainable return as:

$$SEV_{sust} = \left[\sum_{t=0}^{T-1} \frac{B_t - C_t}{(1+r)^t} \right] + \left[\frac{B_T - C_T}{r} \cdot \frac{1}{(1+r)^T} \right] \tag{4}$$

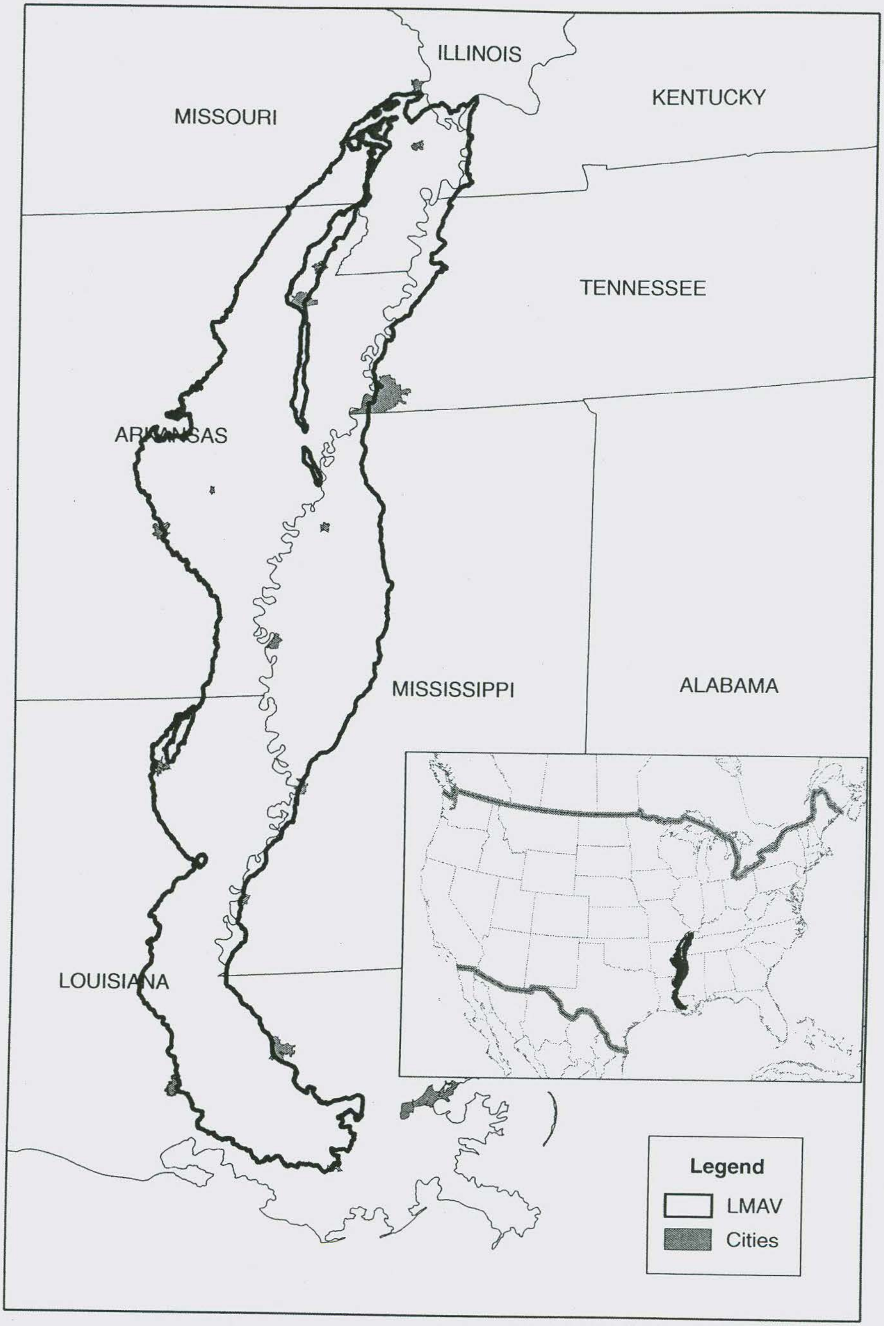

Figure 13.5 Geographic extent of the Lower Mississippi Alluvial Valley (LMAV) (Lower Mississippi Valley Joint Venture, 2002).

A base case SEV was calculated for each scenario assuming no policy interventions and two land capability classes. We also estimated the impacts of government incentive payments, such as fixed direct payments (FDPs) for agricultural crops, forestry and agroforestry systems, WRP and CRP and potential payments for carbon sequestration services.

Real options

In order to solve the partial differential collocation problem for the agriculture versus forestry (or agroforestry) optimal switching problem, we utilized a discrete-time dynamic program (Miranda and Fackler, 2002).[2] The method utilizes *n* nodes to generate a system of *n* linear equations to approximate the value function (equation 2) within the pre-defined state space for each possible action. The action producing the highest value function is preferred. For a relatively simple forestry management regime, such as cultivation of cottonwood for pulpwood with no intermediate thinning, the value function is:

$$f(s,x) = \begin{cases} s^{AG} \mid s^{SA} = 0 \\ sprep \mid s^{SA} = 1 \\ cc \mid s^{SA} = 2or3 \\ GY(s^{SA}) \star s^{TIMB} \mid x = 2 \\ GY(s^{SA}) \star s^{TIMB} + lclear \mid s^{SA} \neq 0 \;\&\; x = 0 \\ 0 \mid otherwise \end{cases} \tag{5}$$

where *sprep* is the cost of site preparation, *cc* is the cost of competition control in years 2 and 3, $GY(s^{SA})$ is the growth and yield function, and *lclear* is the cost of land clearing for agriculture (stump removal). The parameters utilized in the RO model are listed in Table 13.2.

Data

To compensate for lack of data on agroforestry in the LMAV and to validate existing information on forestry and agriculture, we organized three Delphi panels of forestry, agriculture and agroforestry experts to estimate key factors such as yields, costs, prices and management regimes. Additional data were obtained from the NRCS Soil Survey, USDA Agriculture and Resource Management Survey, state crop budget worksheets and Louisiana Quarterly Timber Price Reports. The details of the Delphi methodology and other data sources are described in Frey et al. (2010).

Results

Capital budgeting

BASE CASE

Table 13.3 presents the base case (no incentive payments) results for two Land Capability Classification (LCC) types, LCC3 and LCC5, with the highest potential for agroforestry in the LMAV. LCC3 lands are rarely flooded with poor drainage and severe limitations for agricultural production. LCC5 lands are frequently flooded, very poorly drained soils limited mainly

Table 13.2 Parameters used in the RO models (Frey et al., 2013).

Description	*Source**	*Units*	*Value***	
			LCC3	*LCC5*
Agricultural returns				
Equilibrium returns to agriculture	3, 4	$/ha/yr	382	110
Standard deviation of returns to agriculture	3, 4	$/ha/yr	253	238
Agricultural returns mean reversion rate	2, 4	unitless	0.35	0.35
Timber growth/yield and output prices				
Growth rate of cottonwood in pure plantation	1, 5	ton/yr	19.5	21.9
Growth rate of short-rotation woody crop species	1, 5	ton/yr	21.0	23.2
Growth rate of bottomland oak species in pure plantation	1, 5	ton/yr	7.9	7.9
Equilibrium of mixed hardwood pulpwood price	2, 6	$/ton	5.90	
Standard deviation of mixed hardwood pulpwood price	2, 6	$/ton	1.01	
Ratio of mixed hardwood sawtimber to pulpwood price	2, 6	unitless	5.67	
Ratio of low value to mixed hardwood sawtimber price	1, 6	unitless	0.8	
Ratio of oak to mixed hardwood sawtimber price	1, 6	unitless	1.15	
Timber (pulpwood) price mean reversion rate	2, 6	unitless	0.50	
Other forestry parameters				
Cost of site preparation and planting	1, 7	$/ha	–699	
Cost of competition control	1, 7	$/ha	–32	
Cost of clearing forested land	1	$/ha	–1,356 or –500	
Cost of coppicing cottonwood	1	$/ha	–148	
Yearly administration cost	1, 7	$/ha/yr	–20	
Value of hunting lease in mixed hardwood stand	8	$/ha/yr	15	
Value of hunting lease in cottonwood stand	1	$/ha/yr	7.5	
Relative yield of cottonwood in a cottonwood-oak intercropping system	1, 9		0.90	
Relative yield of oak in a cottonwood-oak intercropping system	1, 9		0.45	
Pecan yield and output prices				
Maximum yield of pecan in orchard (achieved years 19–50)	10	lbs/ha	2,371	
Proportion of maximum yield produced in years 1–7	1	unitless	0	
Proportion of maximum yield produced in years 8–9	1	unitless	0.5	
Proportion of maximum yield produced in year 10	1	unitless	0.63	
Proportion of maximum yield produced in year 11	1	unitless	0.65	
Proportion of maximum yield produced in years 12–16	1	unitless	0.83	
Proportion of maximum yield produced in years 17–18	1	unitless	0.92	
Proportion of maximum yield produced in years 19–50	1	unitless	1	
Equilibrium of pecan nut price	2, 11	$/lb	0.88	
Standard deviation of pecan nut price	2, 11	$/lb	0.32	
Pecan nut price mean reversion rate	2	unitless	0.90	
Other pecan parameters				
Cost of site preparation and planting for pecan	10	$/ha	–1,467	
Yearly fixed costs for pecan management	10	$/ha/yr	–611	
Variable costs for pecan management (mult. by yield rate)	10	$/ha/yr	–982	

Description	*Source**	*Units*	*Value***	
			LCC3	*LCC5*
Agroforestry parameters				
Cost of pruning	1, 7	$/ha	–148	
Relative yield of trees in an alley cropping system	1		0.58	
Ratio of planted acres in an alley cropping system	1	unitless	0.67	
Relative yield of agricultural crop per planted acre in a cottonwood alley cropping system	1	unitless	[0.75, 0.7, 0.65, 0.6, 0.55, 0.5, 0.5, 0.5, 0.5]	
Relative yield of agricultural crop per planted acre in a hard hardwood alley cropping system	1	unitless	[0.8, 0.75, 0.7, 0.065, 0.6, 0.55, 0.55, 0.55, 0.55, 0.55]	
Relative yield of agricultural crop per planted acre in a pecan alley cropping system in year 2	1	unitless	0.67	
Same, year 3	1	unitless	0.63	
Same, year 4	1	unitless	0.60	
Same, year 5	1	unitless	0.57	
Same, year 6	1	unitless	0.53	
Same, years 7–9	1	unitless	0.50	
Same, years 10–18	1	unitless	0.47	
Same, years 19–50	1	unitless	0.43	
Other model parameters				
Discount rate		unitless	0.05	
Minimum agricultural returns in model state space		$/ha	–800	
Maximum agricultural returns in model state space		$/ha	800	
Minimum mixed hardwood pulpwood price in model state space		$/ton	0	
Maximum mixed hardwood pulpwood price in model state space		$/ton	20	
Minimum pecan price in model state space		$/lb	0	
Maximum pecan price in model state space		$/lb	3	
Covariance			0 [0, 0]	

*Number indicates source of the parameter estimate: 1 = Delphi assessment; 2 = mean reversion model; 3 = Monte-Carlo crop switching model; 4 = ERS (2009); 5 = NRCS (2008); 6 = LA DAF (2008); 7 = Smidt et al. (2005); 8 = Hussain et al. (2007); 9 = Gardiner et al. (2004); 10 = Ares et al. (2006); 11 = NASS (2008).[9]
**LCC, Land Capability Classification.

to pasture, range, forestry or wildlife. On LCC3 soils, none of the agroforestry or production forestry systems were competitive with agriculture at any discount rate. However, the SEVs for most of these systems, particularly the agroforestry systems, were substantially higher than on LCC5 soils. In particular, the alley cropping systems had SEVs over $2,000 per hectare at the lowest discount rate (5%).

On the most marginal land (LCC5), at the lowest discount rate (5%), three agroforestry practices and production forestry have higher SEVs than agriculture (soybeans), assuming no policy interventions. At discount rates of 7%–10%, soybean crops dominate all agroforestry and forestry systems on LCC5 lands. The only systems with positive SEVs on LCC5 sites with a 7% discount

Table 13.3 Soil expectation values (SEVs, 2008$ per hectare) for production systems with no policy interventions and varying discount rates, on Land Capability Classes (LCC) 3 and 5 in the Lower Mississippi Alluvial Valley (LMAV) (Frey et al., 2010).

	LCC3			*LCC5*		
Discount rate (%)	*5*	*7*	*10*	*5*	*7*	*10*
Soybeans	5,150	3,679	2,575	925	661	463
Rice	7,771	5,551	3,886	–768	–548	–384
Cottonwood for pulpwood	–257	–499	–689	–338	–625	–844
Cottonwood for sawtimber	1,180	275	–347	1,210	205	–479
Short-rotation woody crop	–2,217	–1,839	–1,565	–2,253	–1,941	–1,713
Hard hardwoods (clearcut)	52	–495	–758	–129	–667	–922
Hard hardwoods (sustainable)	–179	–613	–794	–357	–783	–957
Cottonwood and oak interplanting (clearcut)	158	–495	–885	18	–649	–1,048
Cottonwood and oak interplanting (sustainable)	–12	–589	–915	–158	–743	–1,077
Pecan silvopasture	1,020	–918	–2,255	–28	–1,864	–3,106
Hard hardwoods silvopasture	811	190	–122	321	–246	–513
Pine silvopasture	2,512	951	–12	1,861	404	–477
Hard hardwoods riparian buffer	–333	–652	–784	–510	–822	–947
Cottonwood and oak riparian buffer	–590	–956	–1,138	–769	–1,135	–1,317
Pecan alley crop	2,355	7	–1,640	–235	–2,000	–3,191
Hard hardwoods alley crop	843	275	–13	–8	–467	–656
Cottonwood alley crop	2,144	1,076	362	1,367	393	–234

rate are pine silvopasture, cottonwood alley cropping and cottonwood for sawtimber; at a 10% discount rate, SEVs are negative for all agroforestry and forestry systems.

In the absence of incentive payments, landowners are more likely to adopt agroforestry than conventional forestry on moderately marginal land (LCC3), while on the most marginal land (LCC5) the returns for agroforestry and forestry are similar. Still, the low SEVs for agroforestry compared to agriculture predict little success for agroforestry or forestry in the LMAV. Our estimates are less favorable for forestry than earlier studies (e.g. Anderson and Parkhurst, 2004) because we include tree seedling mortality and recent increase in crop prices.

GOVERNMENT INCENTIVES CASE

Table 13.4 provides SEV results that include government incentive payments (Average Crop Revenue Election [ACRE] and FDP agricultural subsidies and enrollment in WRP and CRP programs). The ACRE and FDP program increase the value of agriculture by 15% on LCC3 and 60% on LCC5 lands. WRP and CRP enrollment is competitive with agriculture on LCC5 land with a slightly lower return from CRP at a 5% discount rate. Higher discount rates make CRP and agriculture less competitive because the WRP easement is paid up front, whereas agriculture and CRP receive annual payments. On LCC3 lands, WRP is less competitive, because of the $2,223 per hectare rate cap, while CRP payments are based on the typical land rental rate, which is higher for LCC3 soils. Therefore, CRP is somewhat more competitive than WRP on moderate soils.

Next, we examine the impacts of a market for carbon sequestration credits. Table 13.5 shows the CO_2 net price per ton that equalizes SEVs for forestry, agroforestry and agriculture, including

Table 13.4 Soil expectation values (SEVs, 2008 $ per hectare, 5% discount rate) for production systems under existing incentive policies: soybeans with Average Crop Revenue Election and Fixed Direct Payment (ACRE and FDP) programs, hard hardwoods with Wetlands Reserve Program (WRP) and hard hardwoods riparian buffer with Conservation Reserve Program Conservation Practice 22 (CRP CP22), on Land Capability Classes (LCC) 3 and 5 in the Lower Mississippi Alluvial Valley (LMAV) (Frey et al., 2010).

	System	*No policy*	*ACRE & FDP*	*WRP*	*CRP*
LCC3	Soybeans	5,150	5,950		
	Hard hardwoods	52		2,233	
	Hard hardwoods riparian buffer	−333			3,696
LCC5	Soybeans	925	1,478		
	Hard hardwoods	−129		2,233	
	Hard hardwoods riparian buffer	−510			2,184

Table 13.5 Break-even net revenue per metric ton CO_2 (2008 $) in various forestry and agroforestry systems compared to soybeans with Average Crop Revenue Election (ACRE) and Fixed Direct Payment (FDP) payments, on Land Capability Classes (LCC) 3 and 5 in the Lower Mississippi Alluvial Valley (LMAV) (Frey et al., 2010).

System	*LCC3*	*LCC5*
Cottonwood for pulpwood	59.58	15.90
Cottonwood for sawtimber	32.47	1.66
Short-rotation woody crop	254.60	102.36
Hard hardwoods (clearcut)	26.59	7.24
Hard hardwoods (sustainable harvest)	15.15	4.54
Cottonwood and oak interplanting (clearcut)	30.87	7.62
Cottonwood and oak interplanting (sustainable)	17.39	4.77
Pecan silvopasture	40.35	12.32
Hard hardwoods silvopasture	29.37	6.61
Pine silvopasture (optimistic returns per head)	35.39	0.00
Hard hardwoods riparian buffer	31.78	10.05
Cottonwood and oak riparian buffer	39.19	13.46
Pecan alley crop	29.42	14.02
Hardwood alley crop	31.55	9.18
Cottonwood alley crop	32.64	0.87

ACRE and FDP payments. At any higher price for CO_2, the respective forestry/agroforestry system becomes more profitable than soybeans. Additional costs/barriers to selling carbon credits from forestry/agroforestry systems, however, may limit participation in CO_2 markets. These include the costs of verifying and registering carbon credits and demonstrating additionality (i.e. proof that the reforestation would not have taken place without the carbon payment).

Real Options

The RO model allowed landowners to adopt the most profitable land use and then convert to other land uses based on knowledge of past returns and expectations of future returns. RO provided a powerful and realistic reflection of the actual decisions that landowners make and extended previous analyses of farm, forest and agroforestry decision making. We found that the decision to switch is driven almost entirely by agricultural returns, given the mean-reversion assumption and the long waiting period between agroforestry establishment and the final timber harvest. For example, if the pulpwood price in the current year was $10/ton and the agricultural returns in the current year were $100 per hectare, continuing in agriculture would be optimal. Switching to alley cropping is only optimal when agriculture loses $800 or more per hectare.

ADOPTION THRESHOLDS

The point at which agroforestry becomes more desirable than agriculture is the 'adoption threshold'. The adoption thresholds are summarized in Table 13.6 for LCC3 and Table 13.7 for LCC5 land. The 'RO value' is the estimate of the value function, *V*(*s*), assuming forestry/agroforestry at the year of site planting and equilibrium prices. This is comparable to the SEV in some cases but allows for increased value from flexibility, including the option to switch back to agriculture. In many cases on recently planted forestry or agroforestry LCC3 land, at equilibrium prices, the optimal decision is to switch back to agriculture immediately.

AEV in Tables 13.6 and 13.7 can be viewed as the 'SEV adoption threshold'. The AEV does not account for the value of being able to wait to convert agricultural land to forestry or select the optimal timber rotation given dynamic timber prices. In most cases, the greater flexibility associated with annual cropping results in lower probabilities of adopting forestry or agroforestry than the simple AEV analysis suggests. Systems with the RO value closest to SEV are the least flexible; most notably, the WRP, which essentially has no flexibility. The RO threshold is lower than the SEV threshold for WRP because we assumed that enrollment in WRP is irreversible and no timber harvest is permitted. The only income allowed after the easement payment is from hunting leases.

Table 13.6 RO and SEV adoption thresholds in terms of agricultural returns per hectare, and RO value and SEV for production forestry and agroforestry systems on land capability class (LCC) 3 land ($/ha/yr) (Frey et al., 2013).

	RO adoption threshold ($/ha/yr) *Land clearing cost:*		*Prob. of crossing threshold* (%)*	*AEV (SEV adoption threshold)*	*RO value, at land clearing cost $1,356/ha*	*SEV***
	$1,356/ha	*$500/ha*				
Wetlands Reserve Program	–1,000	–1,000	<0.1	112	2,236	2,233
Cottonwood	–1,000	–1,000	<0.1	59	5,581***	1,180
Short rotation woody crop	–980	–980	<0.1	–111	6,678***	–2,217
Hard hardwoods	–1,000	–1,000	<0.1	3	5,544***	52
Cottonwood-oak intercrop	–1,000	–1,000	<0.1	8	5,544***	158
Pecan alley crop	–1,000	–1,000	<0.1	118	5,406***	2,355
Hard hardwoods alley crop	–1,000	–900	<0.1	42	6,632***	843
Cottonwood alley crop	–1,000	–1,000	<0.1	107	6,259***	2,144

*At land clearing cost $1,356/ha.

**SEV from Frey et al. (2010).

***The optimal decision at the equilibrium agricultural return value and timber price for a recently planted forestry/agroforestry plot is to return immediately to agriculture.

Table 13.7 RO and SEV adoption thresholds in terms of agricultural returns per hectare, and RO value and SEV for production forestry and agroforestry systems on land capability class (LCC) 5 land ($/ha/yr) (Frey et al., 2013).

	RO adoption threshold ($/ha/yr) *Land clearing cost:*		*Prob. of crossing threshold* (%)*	*AEV (SEV adoption threshold)*	*RO value, at land clearing cost $1,356/ha*	*SEV***
	$1,356/ha	*$500/ha*				
WRP	–240	–240	11	112	2,236	2,233
Cottonwood	140	140	39	61	3,770	1,210
Short rotation woody crop	–550	–550	0.9	–113	1,548	–2,253
Hard hardwoods	–730	–690	<0.1	–6	955	–129
Cottonwood-oak intercrop	–510	–420	1	1	1,469	18
Pecan alley crop	–450	–450	2	–12	1,834	–235
Hard hardwoods alley crop	–830	–600	<0.1	0	1,346	–8
Cottonwood alley crop	270	270	43	68	3,471	1,367

*At land clearing cost $1,356/ha.
**SEV from Frey et al. (2010).

Nevertheless, the returns to WRP enrollment on LCC5 land make it more attractive in the RO model than many forestry and agroforestry systems. For example, on LCC5 sites, the RO adoption threshold was significantly more negative (i.e. more difficult to reach) than the SEV adoption threshold (the AEV) for WRP enrollment, cottonwood timber plantation, short-rotation woody crops, hard hardwood timber plantation, cottonwood-oak intercrop plantation, pecan alley cropping and hardwood alley cropping. On LCC3 land, all RO adoption thresholds were lower than the SEV adoption thresholds.

At first glance, agricultural returns must become negative for it to be optimal to switch to forestry or agroforestry. However, agricultural returns need only turn negative for 1 year for switching to be attractive, and it is certainly feasible that net agricultural returns on these marginal lands will occasionally be negative. On LCC5 sites, three forestry and agroforestry systems have a greater than 10% chance of being adopted on any given plot in any given year. On LCC3 sites, however, no system had a greater than one in a thousand chance of being an optimal choice in any given year.

Approximately 40%–50% of the LMAV is classified as LCC3, and any large-scale effort at reforestation would need to include these soils. To examine the impact of market changes on adoption on LCC3 land, we calculated ROs and AEVs under three scenarios: (1) timber prices double, (2) timber prices double and volatility declines 50% and (3) timber prices double and volatility of agricultural returns increases 50%. We compared adoption thresholds at age 10 and maximum stand age using the equilibrium timber price.

Reducing timber price volatility had little effect on the outcomes in scenarios 1 and 2, and increasing the timber price did not significantly affect adoption thresholds on LCC3 land. All were still below a 0.1% probability of crossing the threshold in any given year.

Under scenario 3 (timber prices double and volatility of agricultural returns increases 50%), changes in adoption thresholds were similar but smaller in magnitude than in Scenarios 1 and 2, suggesting that increased volatility in agricultural returns actually favors agriculture. This is likely due to the assumption of risk neutrality.

Disadoption thresholds for scenarios 1, 2 and 3 were affected more strongly than adoption thresholds for all systems, particularly at older stand ages. In all cases, all three scenarios increased, or kept the same disadoption threshold, meaning forestry and agroforestry would be less likely to be disadopted.

The base case did not include Farm Bill agricultural payments, so a scenario (which we did not model) similar to the present-day scenario which includes Farm Bill agricultural payments but no payments for ecosystem services, would favor agriculture more strongly than the base case. However, when payments for ecosystem services are allowed, forests are more strongly favored than the base case, indicating that these payments can more than counteract farm bill agricultural payments. In fact, these payments have a stronger effect relative to the base case than doubling the timber price in scenario 2 (Frey et al., 2013).

Conclusions

This chapter provides principles, literature and a case study about the economics of agroforestry. The tools presented here can help determine when agroforestry is a feasible option and provide arguments for cases where agroforestry systems are economically, socially and environmentally appropriate, fostering improved sustainable development for landowners, farmers and communities. Agroforestry systems provide multiple outputs, potentially reducing risk and increasing income while also purportedly producing more ecosystem services than conventional agriculture. Our review and case study, however, provide cautionary tales about the limits of agroforestry.

In a few cases where complementary production relationships occur, agroforestry is obviously superior to tree, crop or pasture monocultures. There still may be some resistance to adoption of agroforestry in these cases due to the management challenges with complex systems, but at least the economics may lead to adoption in the long run. In the more common case of competitive production relationships, finding the right mix of inputs and products requires more economic analyses, cautious generalizations about the merits of the cases examined and more extension efforts to encourage farm adoption where agroforestry appears most warranted. The principles we posit here and the literature cited provide a basis for such reviews and recommendations.

The analyses do suggest that to reach its promise, even in cases where the research and economics indicate clear benefits, substantial outreach efforts must occur. The decision to adopt agroforestry systems involves judgments about which systems generate the highest short- and long-run returns, are easiest to manage, readily marketable and fit in with cultural traditions. These factors are not all economic, and farmers may err in evaluating the financials. In some cases, government action and support may be needed to create proper markets and institutions. In almost all cases, better knowledge of inputs, outputs, costs and markets will be required.

The economics and adoption of agroforestry systems will also be determined by the scale of the specific operations. Small-scale subsistence farms in developing countries have higher likelihoods of producing clear, net benefits from agroforestry, based on the need for multiple livelihood products, the availability of on-farm hand and animal labor that can be used with few adverse effects on multiple crops and the benefits of fertilization from trees and/or livestock. These small-scale farm systems can extend beyond the subsistence level with moderate ease in many countries, through production of fruits, nuts, bananas and similar outputs that can be sold in local markets. In these cases, one could say that the findings of economic studies and the adoption of agroforestry systems are often congruent. Farmers have developed these promising systems, economic analyses often support the merits of the systems and outreach programs help extend these systems to a broader range of producers. The environmental benefits of these systems are probably undervalued by the farmer, however, and some type of payments for ecosystem services may be necessary, in most cases, to increase adoption to socially desirable levels.

The discrepancy between the purported income diversification, risk reduction, environmental benefits and the limited farm adoption of agroforestry systems seems to be much wider for medium-sized farms. Numerous studies have found biological and economic benefits from agroforestry systems, which at least have returns greater than monoculture forestry and at times greater than agriculture on poor crop or pasture lands. Yet, adoption rates are often low. These discrepancies suggest either that our science and economic models are faulty, that farmers are irrational, that nonmarket benefits need monetization or that tradition and ease of management trump purely economically rational decision making. A common adage says that if your economic models suggest that farmers are making bad decisions, it is probably the models that are in error.

The case study in the LMAV suggests that agroforestry adoption may be even more difficult than cash-flow analyses alone indicate. For example, the higher opportunity cost to convert back from forests to agriculture reduces agroforestry's desirability. Research on production systems and economics for more mechanized agroforestry systems is still inconclusive about overall merits, so sound economic analyses need to be conducted on individual cases being considered. Our review provides the tools to do so. In situations where large-scale, highly mechanized pure monoculture systems dominate the landscape (as in the LMAV), it will be difficult for mixed agroforestry systems to reverse this situation, except at the windbreak, stream buffer or ornamental level. But those benefits have been well documented, and the economics can be analyzed and promoted.

Additional investments in economics research will be required, however, for agroforestry to achieve its full potential (Mercer and Alavalapati, 2004). Economic analyses need to move beyond enterprise-specific foci and focus on whole-farm analyses as well as move beyond strictly financial analyses to also include the impacts of policy constraints, market failures, farmer preferences and the impact of cultural taboos. Additional dynamic optimization research is needed that includes impacts of stochastic prices, yields and weather variables. Developing time series or panel data sets for econometric analyses is crucial to advancing agroforestry economics research. A large hole in agroforestry economics is studies examining economy-wide impacts of agroforestry adoption using applied general equilibrium analyses such as input-output models, computable general equilibrium models (CGE) and social accounting matrices (SAM). Finally, decisions to adopt agroforestry are complicated by the multiple biophysical, social and economic objectives involved, many of which are difficult to value monetarily. In addition to more research with traditional approaches to nonmarket valuation (contingent valuation, conjoint analysis, travel cost and hedonic approaches), studies using alternative approaches such as the analytical hierarchy process (AHP) should also be expanded (Shrestha, Alavalapati and Kalmbacher, 2004).

Notes

1 Technical efficiency is the purely biophysical effectiveness of production inputs.

2 Because the stand age varies depending on when the landowner switches to forestry, solving the Bellman equation (equation 1) with a Markov-chain dynamic program was not possible.

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