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A real options model to assess the role of flexibility in forestry and agroforestry adoption and disadoption in the Lower Mississippi Alluvial Valley

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Abstract

Efforts to restore the Lower Mississippi Alluvial Valley's forests have not achieved desired levels of ecosystem services production. We examined how the variability of returns and the flexibility to change or postpone decisions (option value) affects the economic potential of forestry and agroforestry systems to keep private land in production while still providing ecosystem services. A real options analysis examined the impact of flexibility in decision making under agriculture, forestry, and agroforestry and demonstrated that adoption of forestry or agroforestry systems is less feasible than would be predicted by deterministic capital budgeting models.

JEL classifications: D01, Q15, Q23, Q24

Keywords: Real options; Agroforestry; Alley cropping; Bottomland hardwoods

1. Introduction

The Lower Mississippi Alluvial Valley (LMAV), the historical floodplain of the lower Mississippi River (Fig. 1), once contained the largest area of bottomland hardwood (BLH) forest in the United States, covering about 10 million ha (King et al., 2006; Twedt and Loesch, 1999). BLH forests provide many crucial ecosystem services such as plant and animal habitat, flood mitigation and groundwater recharge, denitrification and phosphorous sorption, and carbon storage (Walbridge, 1993); however, the existing LMAV forest has been severely reduced through conversion to agriculture (Twedt and Loesch, 1999). Today, only about a quarter of the original BLH area remains and the surviving forests have been degraded by fragmentation, altered hydrology, sedimentation, water pollution, invasive exotic plants, and indiscriminant timber harvesting (King et al., 2006; Twedt and Loesch, 1999).

Because of the numerous ecosystem services provided by BLH, various agencies and organizations have worked for decades to reforest the region. The largest reforestation initiatives for private lands in the LMAV are the Wetlands Reserve Program (WRP) and the Conservation Reserve Program (CRP), both administered by the U.S. Department of Agriculture (King and Keeland, 1999; Llewellyn et al., 1996; Stanturf et al., 1998, 2000). Although approximately 310,000 ha had been reforested on both public and private land by 2005 (King et al., 2006), other areas are characterized by continued deforestation and degradation (Groninger, 2005; Llewellyn et al., 1996; Schoenholtz et al., 2001). The existing forest areas are not large enough to sustain many animal species (Twedt and Loesch, 1999), or support adequate production of important services such as denitrification of runoff and carbon storage (Murray et al., 2009).

It has been suggested that forestry production systems (Gardiner et al., 2004; Stanturf et al., 1998), and agroforestry systems (Dosskey et al., 2012; Twedt and Portwood, 1999), the mixing of trees and agricultural crops and/or livestock on the same piece of land, could augment reforestation efforts in the LMAV by restoring trees on existing agricultural lands, producing reasonable financial returns and some of the same ecosystem services as natural forests, for example, by filtering

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Data Appendix Available Online

A data appendix to replicate main results is available in the online version of this article.

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Fig. 1. Geographic extent of the Lower Mississippi Alluvial Valley (LMAV) (LMVJV 2002).

runoff water and providing habitat buffers and corridors for wildlife species (Dosskey et al., 2012).

The great majority of land in the LMAV is privately owned, as much as 97% by one estimate (NRCS, 2010), and 80–85% of LMAV forests are privately owned (King et al., 2006; Twedt and Loesch, 1999). Therefore, understanding the behavior of private landholders will be essential to the success of any reforestation initiative in the LMAV. Many *ex ante* adoption feasibility studies of forestry and agroforestry systems have used capital budgeting criteria to compare farm and forest investment returns; examples in the LMAV include Amacher et al. (1997) and Frey et al. (2010). Our objective is to extend those analyses by using a real options (RO) approach to model land-allocation decisions, thus providing insight on how risk and variability can affect these decisions. We developed a detailed application of the RO framework to estimate the economic feasibility for forestry and agroforestry systems in the LMAV.

1.1. Background and approach

Deterministic capital budgeting models have been used to estimate profitability and other indicators of expected returns to forestry and agroforestry in the LMAV, such as net present value (NPV). These studies have found that some forest plantations can be competitive with agriculture on marginal, or even average, lands (Amacher et al., 1997; Anderson and Parkhurst, 2004; Frey et al., 2010; Huang et al., 2004; Ibendahl, 2008; Stanturf and Portwood, 1999). Other models have built upon these deterministic capital budgeting models to evaluate the possibility of converting agricultural land to forest, and vice versa. Specifically, Shulstad et al. (1980) utilized a cost/benefit ratio technique to estimate the potential conversion of noncropland to cropland in the LMAV region. More recently, complex computer simulation models, such as the FASOMGHG model (Adams et al., 2005), have been used to forecast large-scale land use change, based on predicted changes in input variables over time. The FASOMGHG model and others assume "deterministic expectations, or 'perfect foresight'" (Adams et al. 2005, p. 53).

However, variability in returns and decision-making flexibility may also play a role in private land-use decisions. A good land manager will value the option to change or postpone decisions in order to adapt to changing conditions. Certain land-use practices may provide more flexibility to alter decisions than others. Deterministic models, including those described by Frey et al. (2010), Shulstad et al. (1980), and Adams et al. (2005) are only able to incorporate changing conditions in the sense of changes in today's conditions that may be expected in the future, and can permit decisions that adapt to these circumstances. However, deterministic models cannot predict which decisions would be optimal under risky or uncertain conditions. In deterministic models, decision makers are assumed to have perfect foresight of future conditions, or as Adams et al. (2005, p. 53) puts it, "expected future prices and the prices that are realized in the future are identical." In contrast, RO techniques can be used to estimate the value created by having flexibility when facing uncertain future conditions. Utilizing both stochastic and deterministic models can provide important insights about financial decisions.

Our research built upon previous deterministic capital budgeting research related to the adoption potential of a variety of agroforestry and forestry systems in the LMAV (Frey et al., 2010) by developing and applying a stochastic RO model that includes the value of flexibility in land-use choices by private landowners. Both agriculture and forestry (and agroforestry) systems offer at least some flexibility in certain decisions. RO research has demonstrated that the decision to harvest timber will be determined by the state of variable timber prices, rather than set at a fixed, pre-determined stand age; that is, if prices are not favorable, a landowner can choose to postpone the harvest (Haight and Holmes, 1991; Plantinga, 1998). Another flexible decision is whether and when to convert land from agriculture to forestry. A landowner may easily put off the decision to reforest/afforest and continue farming until the following year, depending on the relative prices and yields of agricultural crops and timber. Behan et al. (2006) and Wiemers and Behan (2004) used RO to show that it is optimal for a farmer to wait longer to reforest/afforest than is estimated by a standard discounted cash-flow framework because of establishment costs and the relative irreversibility of the decision to switch to forestry.

Although the decision to switch to forestry was modeled as irreversible by Behan et al. (2006) and Wiemers and Behan (2004) because of regulations in Europe and the forest carbon offset market, this is not generally true. Land conversion from forest use to agriculture involves numerous up-front costs, such as stump removal, that are barriers to shifting to agriculture, but the barriers are not insurmountable. We therefore modeled the decisions to switch from conventional agriculture to forestry (or agroforestry) and from forestry (or agroforestry) to agriculture as a dichotomy of choices that allows switching from one land use to another, and switching back again; that is, including both the adoption and disadoption choices for forestry/agroforestry. Although studies have shown that adoption and disadoption are both important choices that land managers make (German et al., 2006; Kiptot et al., 2007), our review of published forestry and agroforestry economics literature found no stochastic models that explicitly take this dichotomy of choices into account.

Flexibility in response to risk can impact decisions. The flexibility to put off reforestation provides additional value to agriculture, and the flexibility to postpone timber harvest adds value to forestry/agroforestry. Because previous research related to risk and flexibility with stochastic models has not included these decisions in a single model, it is not known how the relative magnitudes of the value of flexibility, or option value, compare. Depending on which system provides more option value, forestry (and agroforestry) will be either more or less likely to be adopted than predicted by deterministic models.

By including the possibility of switching back to agriculture after reforestation in a stochastic RO model, our model uses a novel approach with a well-tested method. We include three forms of flexibility: the flexibility to stay in agriculture, to delay timber harvests depending on crop and timber prices, and to harvest the timber but remain in forestry by replanting the trees. In the last case, the landowner incurs the cost of tree establishment, but not the cost of clearing the land.

2. Real options

RO analyses are based upon the Bellman equation, which utilizes the principle that decision makers choose a management regime to maximize the sum of rewards (profit, utility, etc.) at the present, and discounted expected future rewards:

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

where $V_t(s)$ is the value function denoting the total value of the land at time t in state s, $f(s,x)$ is the reward function that gives the financial returns by choosing action x under state s, $\delta = \frac{1}{1+\rho}$ (or $e^{-\rho}$ for continuous discounting) is the discount factor (where ρ is the traditional annual discount rate), and $E[\cdot]$ is the expectation operator. T is the time horizon of the management question; $g(\cdot)$ is the transition function from states s, actions x, and some shock ε (variability, risk) in year t to states in year $t+1$. The key difference between the Bellman equation and cash-flow counterparts is the recursive nature of the decision-making process. It assumes that decisions made in year t can also be put off until year $t+1$, up until year T, much like a land manager could continue to wait to decide whether or not to reforest or cut timber, based on the conditions in the current year; that is, there is flexibility in the decision-making process.

Most forest harvesting RO models have used a Markov-chain Monte Carlo approach to solve the Bellman equation. However, recently partial differential methods have come into favor because of improved precision and other factors (Insley and Rollins, 2005). We utilized a partial differential method in part for these reasons, but also because the backward-moving dynamic program utilized to solve the Markov-chain process would have required knowledge of the time horizon, T. Since, in our model, the stand age in year t varied depending on what year the landowner switches to forestry, it would be impossible to model in a Markov-chain dynamic program.

For an infinite-horizon model, as modeled by the partial differential method, all points in time become equivalent and the Bellman equation simplifies to (Miranda and Fackler, 2002, pp. 190–191):

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

One way to solve for the value function $V(s)$, and thus determine the optimal regime for each state, $x(s)$, is to use a partial differential collocation method, as demonstrated in Miranda and Fackler (2002, pp. 227–238).

3. Data

3.1. Delphi assessment

Agroforestry is not currently widely practiced in the LMAV, and there are few research or demonstration plots. Due to lack of data on agroforestry production in the LMAV, and to validate existing information on forestry and agriculture, we organized three panels of forestry, agriculture, and agroforestry experts in the LMAV for a Delphi assessment[1] to estimate key factors such as yields, costs, prices, and management regimes. The Delphi methodology used in this study is described in Frey et al. (2010).

Land Capability Classification (LCC), "a system of grouping soils primarily on the basis of their capability to produce common cultivated crops . . ." (NRCS, 2007) was selected to classify sites in the LMAV.[2] LCC combines numerous factors, including drainage class, flooding frequency, etc., to determine general productivity. We focused our analysis on LCC 3 and 5, where trade-offs between agriculture and forestry or agroforestry are most likely to exist (Frey et al., 2010). LCC 3 lands

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[1] Dalkey and Helmer (1963) of the RAND Corporation created the Delphi method as a technique for fostering dialogue among a panel of knowledgeable subjects to work toward a consensus. The methodology utilizes an iterative approach and anonymity among panelists.

[2] LCC range from 1 to 8, with LCC 1 soils being the most well-suited for agricultural purposes and LCC 8 the least. LCC 1 and 2 include the most productive lands, about 25% of LMAV area (NRCS, 2008), and are therefore unlikely to be converted to any type of forestry or agroforestry system. LCC 3 and 5 soils together account for approximately 60% of LMAV area (NRCS, 2008) and include moderately productive to marginal soils. Other classes (LCC 4, 6–8) have limited area in the LMAV or virtually no potential for agriculture.

Table 1
Forestry and agroforestry systems selected for financial analysis by the Delphi assessment panels

System name	Species 1	Species 2	Max stand age in model	Prunings	Thinnings	Hunting lease (2008 $/ha/year)	Management notes
Wetlands Reserve Program	Hard hardwood**						
Cottonwood plantation	Eastern cottonwood (*Populus deltoides*)		35	None	2	7.50	
Short-rotation woody crop	Soft hardwood*		5	None	None	None	Coppice and resprout (with resprout control) at end of rotation
Hard hardwoods plantation	Hard hardwood**		50	None	2	15.00	After 50 years, the site could be clear-cut or managed with small, periodic, sustainable harvests, maintaining a mature intact stand.
Cottonwood and oak interplanting (Gardiner et al., 2004)	Eastern cottonwood	Oak***	50	None	Oaks 2, cottonwood 2 coppices	15.00	Cottonwood clear-cut after 20 years to allow oak growth. Harvest options same as above.
Pecan alley cropping	Pecan	Agricultural crop	50	None	None	None	Nut harvest begins age 8, timber not sold.
Hard hardwoods alley cropping	Hard hardwood**	Agricultural crop	50	3	2	15.00	Alley crop years 0–10, hunting lease after
Cottonwood alley cropping	Eastern cottonwood	Agricultural crop	23	3	3	7.50	Alley crop years 0–9, hunting lease after.

*Soft hardwood: Eastern cottonwood (*Populus deltoides*), black willow (*Salix nigra*), or American sycamore (*Platanus occidentalis*).

**Hard hardwood: Nuttall oak (*Quercus texana*), cherrybark oak (*Q. pagoda*), water oak (*Q. nigra)*, green ash (*Fraxinus pennsylvanica*), baldcypress (*Taxodium distichum)*, others, or a mix of species.

***Oak: Nuttall oak, cherrybark oak, water oak, or other bottomland oak species.

have "severe limitations that reduce the choice of plants or require special conservation practices" (NRCS, 2007) and typically consist of rarely flooded lands with poor drainage in the LMAV (NRCS, 2008). LCC 5 lands have "limitations that limit their use mainly to pasture, range, forestland, or wildlife food and cover" (NRCS, 2007) and typically consist of frequently flooded, very poorly drained land (NRCS, 2008).

The eight agroforestry and forestry systems selected for assessment with the RO model are listed in Table 1. They include hardwood forestry systems and alley cropping agroforestry systems. Alley cropping systems include agricultural crops planted in the "alleys" between rows of trees.

An important input into the RO model is the cost of clearing forestland to switch from forest land use to agriculture, since it is a barrier to switching between land uses. This value was estimated by the Delphi panel to have a median of approximately $1,356/ha.

3.2. Agricultural returns

Under a Memorandum of Understanding with USDA National Agricultural Statistics Service (NASS) and the Economic Research Service (ERS), we utilized data on farm-level and aggregate revenues in LMAV counties for the three major crops (cotton, rice, and soybeans) for the years 1996–2007 from the Agricultural Resource Management Survey (ARMS) Phase III (ERS, 2009) to estimate agricultural return means and variability. This is the most complete farm-level data set of agricultural yields available in the region. External sources were used to validate estimates of returns to agricultural crops (MSU, 2008; NRCS, 2008; Paxton, 2009; UArk, 2009; UM, 2009; UTK, 2009).

3.3. Timber and nut prices and yields

Annual timber and pulpwood prices were available from the Louisiana Quarterly Report of Forest Products (LAQRFP) for the years 1955–2007 (LA DAF, 2008). Following Yin and Caulfield (2002), we utilized timber prices from 1991 to 2007 to generate our estimates of the price mean and variability. National prices for pecan were obtained from the NASS's Noncitrus Fruits and Nuts Summary (NASS, 2008). Estimates of cottonwood growth and yield were taken from Cao and Durand (1991) whereas Baker and Broadfoot (1979) provided guidelines for estimating growth and yield for numerous hardwood species.

4. Methods

To estimate the underlying parameters for the RO model, it was necessary to undertake two preliminary analyses. First, we estimated a mean-reversion model of crop returns, and timber and pecan prices using aggregate time-series data. Then, we conducted a Monte Carlo simulation of multivariate crop returns on a single field to estimate the increase in profitability that a farmer might obtain by switching between various crops. The methodology and results of these preliminary analyses are discussed in more detail in Frey (2009).

4.1. Assumptions

Numerous studies have attempted to provide evidence to support or reject various hypothesized distributions of agricultural and timber returns (see Goodwin and Ker, 2002). Such a detailed assessment is beyond the scope of this research. Rather, we made certain simplifying assumptions, in order to make the RO simulations computationally tractable.

Agricultural input prices in the LMAV have shown a relatively steady and predictable trend over time compared to net returns (ERS, 2009). This suggests that most of the variability in agricultural net returns comes from the variability in output prices and productivity, rather than input prices. Therefore, we assumed that the variability of net returns in agriculture is completely due to the variability in revenues (output price times quantity), rather than variability in costs.

In order to model potential for adoption of alternative production systems while taking into account stochastic returns through time, it was necessary to first create a credible model of how returns evolve over time. Therefore, we assumed that agricultural returns, timber prices, and nut prices followed a mean-reverting process. Typically, RO models have utilized the underlying models of either geometric Brownian motion (GBM) or mean reversion. A mean-reverting process is a more theoretically plausible alternative for modeling agricultural and timber product prices, because when returns to a particular commodity are relatively high, more suppliers are likely to enter the market, putting downward pressure on prices and returns, and the opposite when returns are low (Bessembinder et al., 1995; Insley and Rollins, 2005; Isik, 2006; Schwartz, 1997). Parameters for mean reversion of timber and nut prices, and agricultural returns were estimated using an Ornstein–Uhlenbeck model:

$$s_{t+1} = s_t + \alpha\,[eq - s_t] + \sigma \cdot \varepsilon_t, \tag{3}$$

where s_t is the price or returns in time t, eq is the mean or equilibrium of the mean-reverting process, α is the mean-reversion rate, ε is a random shock variable, assumed to be distributed normally, and σ is the square root of the variance of the shock. We had very little data with which to estimate a covariance between the shocks in agricultural returns and timber (or nut) prices. The data that were available through ARMS suggested that the covariance may be relatively small, so we assumed the covariance to be zero.

Because timber grows over numerous years, variability in growth and yield from year to year due to weather may tend to average out over time. Also, input price trends for forest plantation management are relatively stable and small compared to timber prices (Smidt et al., 2005). We therefore assumed that variability in timber returns is mostly due to variability in timber prices. Therefore, timber volume growth was modeled deterministically and price per unit volume was modeled as a mean-reverting process. We also assumed that sawtimber and pulpwood prices were perfectly correlated, that is, the two prices always maintained the same relative values (sawtimber price per ton[3] is always exactly x times the pulpwood price). This is not true in the real world, but an important simplifying assumption which allows for a single stochastic variable to model both pulpwood and pulpwood prices. Finally, we assumed a discount rate of 5%.

4.2. RO model

4.2.1. Systems analyzed

The RO model was used to find the level of agricultural net returns (or losses) at which a land manager would find it optimal to switch from agriculture to the forestry/agroforestry systems in Table 1 (adoption) or vice versa (disadoption). In addition to those systems, we assessed the adoption potential of BLH forest plantation through the WRP. The WRP is the principal program for reforesting private lands via permanent easements which provide a one-time easement payment and 100% of the restoration costs. We assumed a permanent easement payment of $2,223 per hectare, the geographic rate cap used in Mississippi and Louisiana; no timber harvest or livestock grazing is allowed on WRP lands, but the landowner is allowed to sell a hunting/recreation lease. These average about $15 per hectare per year in a core section of the LMAV (Hussain et al., 2007). For certain tree species and systems, we adjusted lease prices, as shown in Table 1.

4.2.2. Operationalizing the partial differential collocation problem

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, 1997). The method utilizes n nodes to generate a system of n linear equations to approximate the value function (2) within the pre-defined state space for each possible action. The action with the highest value of the value function is determined to be the optimal action at each node.

It was necessary to program the state set, S; the action set, X; the state transition function, $g(\cdot)$; and the reward function, $f(\cdot)$ for each land use we tested as an option to agriculture. 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. The parameters utilized in the model are described below and their values listed in Table 2.

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[3] We used prevailing units for timber and carbon markets in the US South, specifically US or short "tons" for timber, and metric "tonnes" for carbon.

Table 2
Parameters used in the real options models

Variable	Description	Source*	Units	Value	
				LCC 3	LCC 5
Agricultural returns					
ageq	Equilibrium returns to agriculture	3, 4	$/ha/year	382	110
agsigma	Standard deviation of returns to agriculture	3, 4	$/ha/year	253	238
a1	Agricultural returns mean-reversion rate	2, 4	unitless	0.35	0.35
Timber growth/yield and output prices					
ctwtons	Growth rate of cottonwood in pure plantation	1, 5	ton/ha/year**	19.5	21.9
srwctons	Growth rate of short-rotation woody crop species	1, 5	ton/ha/year**	21.0	23.2
oaktons	Growth rate of bottomland oak species in pure plantation	1, 5	ton/ha/year**	7.9	7.9
timbeq	Equilibrium of mixed hardwood pulpwood price	2, 6	$/ton	5.90	
timbsigma	Standard deviation of mixed hardwood pulpwood price	2, 6	$/ton	1.01	
pulpsaw	Ratio of mixed hardwood sawtimber to pulpwood price	2, 6	unitless	5.67	
lowvaluemixed	Ratio of low value to mixed hardwood sawtimber price	1, 6	unitless	0.8	
oakmixed	Ratio of oak to mixed hardwood sawtimber price	1, 6	unitless	1.15	
a2	Timber (pulpwood) price mean-reversion rate	2, 6	unitless	0.50	
Other forestry parameters					
sprep	Cost of site preparation and planting	1, 7	$/ha	−699	
cc	Cost of competition control	1, 7	$/ha	−32	
lclear	Cost of clearing forested land	1	$/ha	−1,356 or −500	
coppice	Cost of coppicing cottonwood	1	$/ha	−148	
admin	Yearly administration cost	1, 7	$/ha/year	−20	
lease	Value of hunting lease in mixed hardwood stand	8	$/ha/year	15	
ctwlease	Value of hunting lease in cottonwood stand	1	$/ha/year	7.5	
cointerctwadj	Relative yield of cottonwood in a cottonwood-oak intercropping system	1, 9		0.90	
cointeroakadj	Relative yield of oak in a cottonwood–oak intercropping system	1, 9		0.45	
Pecan yield and output prices					
pecanyield	Maximum yield of pecan in orchard (achieved years 19–50)	10	lbs/ha	2,371	
yieldrate (1–7)	Proportion of maximum yield produced in years 1–7	1	unitless	0	
yieldrate (8–9)	Proportion of maximum yield produced in years 8–9	1	unitless	0.5	
yieldrate (10)	Proportion of maximum yield produced in year 10	1	unitless	0.63	
yieldrate (11)	Proportion of maximum yield produced in year 11	1	unitless	0.65	
yieldrate (12–16)	Proportion of maximum yield produced in years 12–16	1	unitless	0.83	
yieldrate (17–18)	Proportion of maximum yield produced in years 17–18	1	unitless	0.92	
yieldrate (19–50)	Proportion of maximum yield produced in years 19–50	1	unitless	1	
nuteq	Equilibrium of pecan nut price	2, 11	$/lb	0.88	
nutsigma	Standard deviation of pecan nut price	2, 11	$/lb	0.32	
a3	Pecan nut price mean-reversion rate	2	unitless	0.90	
Other pecan parameters					
pecansprep	Cost of site preparation and planting for pecan	10	$/ha	−1,467	
pecanfixed	Yearly fixed costs for pecan management	10	$/ha/year	−611	
pecanvariable	Variable costs for pecan management (mult by yieldrate)	10	$/ha/year	−982	
Agroforestry parameters					
prune	Cost of pruning	1, 7	$/ha	−148	
tonsadj	Relative yield of trees in an alley cropping system	1		0.58	
pa	Ratio of planted acres in an alley cropping system	1	unitless	0.67	
ctwry	Relative yield of agricultural crop per planted acre in a cottonwood alley cropping system	1	unitless	[0.75 0.7 0.65 0.6 .55 .5 .5 .5 .5]	
oakry	Relative yield of agricultural crop per planted acre in a hard hardwood alley cropping system	1	unitless	[0.8 0.75 0.7 .065 0.6 0.55 0.55 0.55 0.55 0.55]	
pary (year 2)	Relative yield of agricultural crop per planted acre in a pecan alley cropping system in year 2	1	unitless	0.67	
pary (3)	Same, year 3	1	unitless	0.63	
pary (4)	Same, year 4	1	unitless	0.60	

(*Continued*)

Table 2
Continued

Variable	Description	Source*	Units	Value	
				LCC 3	LCC 5
pary (5)	Same, year 5	1	unitless	0.57	
pary (6)	Same, year 6	1	unitless	0.53	
pary (7–9)	Same, years 7–9	1	unitless	0.50	
pary (10–18)	Same, years 10–18	1	unitless	0.47	
pary (19–50)	Same, years 19–50	1	unitless	0.43	
Other model parameters					
rho	Discount rate		unitless	0.05	
agmin	Minimum agricultural returns in model state space		\$/ha	−800	
agmax	Maximum agricultural returns in model state space		\$/ha	800	
timbmin	Minimum mixed hardwood pulpwood price in model state space		\$/ton	0	
timbmax	Maximum mixed hardwood pulpwood price in model state space		\$/ton	20	
nutmin	Minimum pecan price in model state space		\$/lb	0	
nutmax	Maximum pecan price in model state space		\$/lb	3	
covar	Covariance			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).
** We used prevailing units for timber and carbon markets in the US South, specifically US or short "tons" for timber, and metric "tonnes" for carbon.

4.2.3. *State variables*

There were three state variables in the model: returns to agriculture, timber price, and stand age. In cases with pecan, timber price was replaced with nut price. The first state variable, s^{AG} represented the yearly net returns to agriculture per hectare. The second state variable, s^{TIMB} represented the price of pulpwood per ton (or s^{NUT}, the price of pecans per pound). To estimate sawtimber price, we multiplied s^{TIMB} by the ratio of the mean sawtimber price to the mean pulpwood price, and included an adjustment factor to account for certain species whose sawtimber prices are substantially different from mixed hardwood. In the model, the state space needed to be large enough to allow for a wide range of variability around the equilibrium agricultural net returns value and the equilibrium timber price, whereas at the same time being a small enough range to allow reasonable confidence in the estimate. The state space was chosen to range from −\$800 (variable *agmin*) to \$800 (*agmin*) per hectare per year for agricultural returns and from \$0 (*timbmin)* to \$20 (*timbmax)* per ton of pulpwood. In models with pecans, nut price was allowed to range from \$0 (*nutmin*) to \$3 (*nutmax*) per pound.

The final state variable was a variable representing land use and stand age. This is a discrete variable, s^{SA}, ranging from 0 to the maximum allowable stand age (*maxsa*). If s^{SA} is 0, the land is in agriculture. If s^{SA} is 1, this represents the beginning of the first year of a stand of trees, whether it is forestry or agroforestry. In the model, the state space ranged from 0 to the maximum stand age for each system (Table 1). The term "maximum stand age" does not mean that the model required cutting the trees once this age is reached (this would prevent the flexibility in decision making that was sought). Rather, it simply represents the end of the state space in the computer model. Although the stand should be allowed to continue infinitely as prices fluctuate, the model must be finite. In the model, if the stand reaches the maximum stand age, and is not cut, then the state transition function returns the stand back into the same stand age the following year (see section below on state transition function), meaning the timber volume reaches a constant level. In the case of species that are typically managed as uneven-age stands (hard hardwoods such as oaks), the model allows a small annual harvest equal to the mean annual volume increment when the stand is at the maximum allowable age, without clear-cutting. With species that are typically managed as even-age stands (i.e., soft hardwoods such as cottonwood), only clear-cut harvest was allowed (except for pulpwood thinning), but the clear-cut may be delayed if prices are not beneficial.

4.2.4. *Decision variable*

The decision variable, x, is defined as 0 for remaining in agriculture (if $s^{SA} = 0$) or a timber harvest with subsequent change to agriculture (if $s^{SA} \neq 0$), 1 for switching from agriculture to forestry or maintaining the forest stand for one more year, or 2 for a timber harvest with subsequent replanting. As long as $x = 1$, s^{SA} will continue to increase until the maximum allowed stand age is reached.

The model is allowed to choose $x = 0$, 1, or 2 at any state in order to maximize the value function. That is, there are no predetermined years for switching from agriculture to forestry or back. Optimal timber harvest or forest plantation is determined on the basis of all the state variables: agricultural net returns, timber price, and stand age.

Although the model allows for switching between forestry and agriculture at any time, there are monetary barriers to going back and forth. To switch from agriculture to forestry involves site preparation and tree planting. To switch back involves removing the stumps and roots of the trees. These barriers make a farmer more likely to stay in the same regime that he is in currently rather than switching back and forth with every minor shift in prices.

4.2.5. Value function

For a relatively simple forestry management regime, such as cultivation of cottonwood for pulpwood with no intermediate thinning, the reward function is

$$f(s,x)=\begin{cases} s^{AG} \mid s^{SA}=0 \\ sprep \mid s^{SA}=1 \\ cc \mid s^{SA}=2\ or\ 3 \\ GY(s^{SA})*s^{TIMB} \mid x=2 \\ GY(s^{SA})*s^{TIMB}+lclear \mid s^{SA}\neq 0 \quad \& \quad x=0 \\ 0 \mid otherwise, \end{cases} \tag{4}$$

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 of stand age, and *lclear* is the cost of land clearing for agriculture (stump removal), all on a per hectare basis.

4.2.6. State transition function

The state transition function assumes that agricultural net returns and timber prices follow a mean-reverting random walk. This means that although agricultural annual net returns, timber price, or nut price are serially correlated, they tend toward a long-run equilibrium, or mean, value (variables *ageq*, *timbeq*, *nuteq*) over time, at rates α^{AG}, α^{TIMB}, α^{NUT}. The randomness of the walk is driven by a shock, ε. The ε's for agriculture net returns and timber price were modeled with zero covariance, and under the assumption of mean reversion, as noted earlier. The state transition function followed the Ornstein–Uhlenbeck model (3) for agricultural returns and timber (and nut) prices:

$$\begin{aligned} s_{t+1}^{AG} &= s_t^{AG}+\alpha^{AG}\left(ageq-s_t^{AG}\right)+\varepsilon^{AG} \\ s_{t+1}^{TIMB} &= s_t^{TIMB}+\alpha^{TIMB}\left(timbeq-s_t^{TIMB}\right)+\varepsilon^{TIMB} \\ s_{t+1}^{SA} &= \begin{cases} 0 \mid x=0 \\ s_t^{SA}+1 \mid x=1 \quad \& \quad s_t^{SA}<MAXSA \\ MAXSA \mid x=1 \quad \& \quad s_t^{SA}=MAXSA \\ 1 \mid x=2. \end{cases} \end{aligned} \tag{5}$$

The mean, mean-reversion rate, and variance of the shock of s^{AG} are defined by estimation of a mean reversion and Monte Carlo model discussed in Frey (2009). The mean, mean-reversion rate, and variance of the shock of s^{TIMB} are determined by estimation of a mean-reversion model for timber prices (Frey 2009).

We included a sensitivity analysis of the cost of clearing land (stump removal, etc.) that would be necessary to switch from forestry to agriculture. The estimate of \$1,356/ha for this cost was estimated with a low degree of confidence by the Delphi panel. As this cost creates a barrier to switching land uses, it was thought that it might have an important effect on land manager behavior.

In sum, this RO approach allowed us to model the ability of landowners to utilize the most profitable land use, and switch between those land uses based on their expectations for future net returns based on past experience. This new approach provided a powerful and realistic reflection of the actual decisions that landowners make, and extended previous analyses of farm, forest, and agroforestry decision making.

4.3. Market shifts and policy programs

It is possible that market changes could lead to a new market equilibrium that could make forestry and agroforestry more competitive. We re-evaluated the RO simulation under various alternative scenarios for LCC 3 land, which included changes to the following parameters in Table 2: Scenario 1, timber equilibrium prices (*timbeq*) doubled; Scenario 2, timber equilibrium prices doubled and timber price volatility decreased by 50% in terms of standard deviation (*timbsigma*); Scenario 3, timber equilibrium prices doubled and agricultural returns volatility increased by 50% (*agsigma*). Many other possible scenarios could be tested, but these were selected to compare alternative conditions under which agroforestry and forestry might be competitive on average (LCC 3) land. We compared the adoption threshold, and the disadoption thresholds at age 10 and maximum stand age, at the equilibrium timber price.

Also, our base RO model did not take into account the effects of policy programs that provide payments to farmers. Such programs include catastrophic insurance coverage, the average crop revenue election (ACRE), and fixed direct payments (FDP). Including the formulas for these programs would have complicated the stochastic model significantly. However, the effects of the ACRE and FDP programs in the deterministic sense are examined in Frey et al. (2010). The ACRE and FDP programs together increase agricultural net returns by about 15% on LCC3 land and 60% on LCC5 land over the long run. Furthermore, these two programs together with the catastrophic insurance coverage would significantly reduce risk. On the other hand, there are possibilities for incentives payments for forestry or agroforestry. We have already considered the WRP as an option in the base case; but of additional interest is the possibility of future mechanisms to pay for ecosystem services. These include carbon sequestration by capturing carbon dioxide from the atmosphere, and nitrogen mitigation by removing agricultural land from production and denitrification of runoff (Frey et al., 2010; Murray et al., 2009).

There are many different policy options for payment for ecosystem services, some of which are market-based and allow prices to vary. However, experience to date shows that many landowners or managers would not face the risk in prices every year; it is common to fix prices contractually with a buyer or broker. On the other hand, under this scenario, there may be a significant contractual penalty for returning the land to agriculture. We evaluated the RO model under Scenario 4 for LCC 3 land: a 15% increase in agricultural net returns (*ageq*) and 15% decrease in volatility (*agsigma*) consistent with the ACRE and FDP programs, along with annual payments for nitrogen and carbon mitigation. For carbon, we used a conservative net value of \$1/metric tonne[4] CO_2 and the method of estimation of CO_2 sequestered from Frey et al. 2010. We assumed carbon sequestration of 12.1 tonnes CO_2eq/ha/year for cottonwood systems, and 2.4 tonnes CO_2eq/ha/year for hard hardwood systems. For nitrogen, we assumed a reduction of 40 kg/ha in nitrogen runoff from (i) eliminating 37 kg/ha of N loss by removing land from agricultural production, and (ii) a conservative estimate of 3 kg/ha of denitrification of runoff (Murray et al., 2009), and a conservative net value of \$5/kg N. We assumed total repayment of the current timber rotation's ecosystem services payments plus a 50% penalty if forestland is converted to agriculture. Pecan-based systems were assumed to not receive payments for ecosystem services, since they are not perceived to have large potential for CO_2 sequestration or N mitigation relative to other forestry or agroforestry systems.

5. Results and Discussion

5.1. Delphi assessment, mean-reversion model, and crop switching model

The outputs of the Delphi assessment, mean-reversion model, and crop switching model became the parameter inputs into the RO model (Table 2). The methods and results of these preliminary analyses are discussed in more detail in Frey et al. (2010) and Frey (2009).

5.2. RO model

The RO model was used to compare each of the various forestry and agroforestry systems proposed by the panel of experts (Table 1) to agriculture, to evaluate potential in the LMAV. These systems are consistent with those evaluated with a deterministic capital budgeting model in Frey et al. (2010).

5.2.1. Resolution of results

Understanding the constraints on the outputs of the RO is important in evaluating the results. Because our model utilized a three-dimensional state space rather than the typical two-dimensional state space in many RO models, computer memory became an issue. Only a relatively limited number of linear functions, and thus a limited number of nodes, could be utilized; otherwise, the memory constraints would be exceeded. The model found the optimal decision at each node in the state space, forming a grid of optimal decisions. Because the number of nodes had to be limited, the distance between each node was relatively far, meaning resolution was relatively low.

In order to estimate the adoption threshold (described below) with more precision, once we had found an approximate value for the threshold, we ran the simulation a second time within a narrower range of values. However, the efficacy of this approach is somewhat limited, because the state space must necessarily include values of the state variables both above and below the equilibrium value, otherwise problems arise at the boundaries of the state space. Therefore, if the approximate threshold value is found to be far below the equilibrium agricultural returns, re-running the simulation does little to improve resolution.

Regardless of the resolution, because the underlying assumptions of the RO model (e.g., normality of the shock variable ε) have not been rigorously tested, one should not consider the estimate of the adoption or disadoption threshold as a precise measure. Rather, it should be seen as an indication of the relative adoptability or disadoption risk of the various systems, and to compare with the deterministic capital budgeting models.

5.2.2. Decision matrix

Figs. 2–5 provide a visual representation of one of the outputs of the RO model hard hardwood alley cropping system on LCC 5 land. These figures represent the optimal decision matrix (X) for two dimensions (agricultural returns and timber prices) of the entire modeled state space, for four different stand ages (the third dimension). All four figures utilize the same axes in the two dimensions, so they are easily comparable. Fig. 2 shows the optimal decision matrix for agriculture versus alley cropping, assuming that the land being considered for conversion to alley cropping is currently in agriculture ($s^{SA} = 0$). The black-colored cells represent the points at which the optimal decision is to remain in agriculture, whereas the white colored cells represent the points at which it is optimal to switch to alley cropping. So, if the pulpwood price in the current year was \$10/ton and the agricultural returns in the current year were \$100 per hectare, it would be optimal for a farmer to continue agriculture. If, however, the agricultural returns this year were a loss of about \$800 per hectare, then it would be optimal to switch to alley cropping.

The horizontal division between the white and black cells suggests that the decision to switch is driven almost entirely by agricultural returns; otherwise, the division would be more diagonal. The reason for this is the assumption of mean reversion and the relatively long waiting period between agroforestry establishment and the eventual timber harvest. That is to say, regardless of today's timber price, given the assumption of mean reversion, the expected value of timber prices far in the future would be very close to the equilibrium or mean timber price.

The level at which a farmer crosses from nonadoption of alley cropping to adoption (moving downwards on the graph) we call the "RO adoption threshold." Because the level of this threshold was largely unaffected by timber prices, it can be

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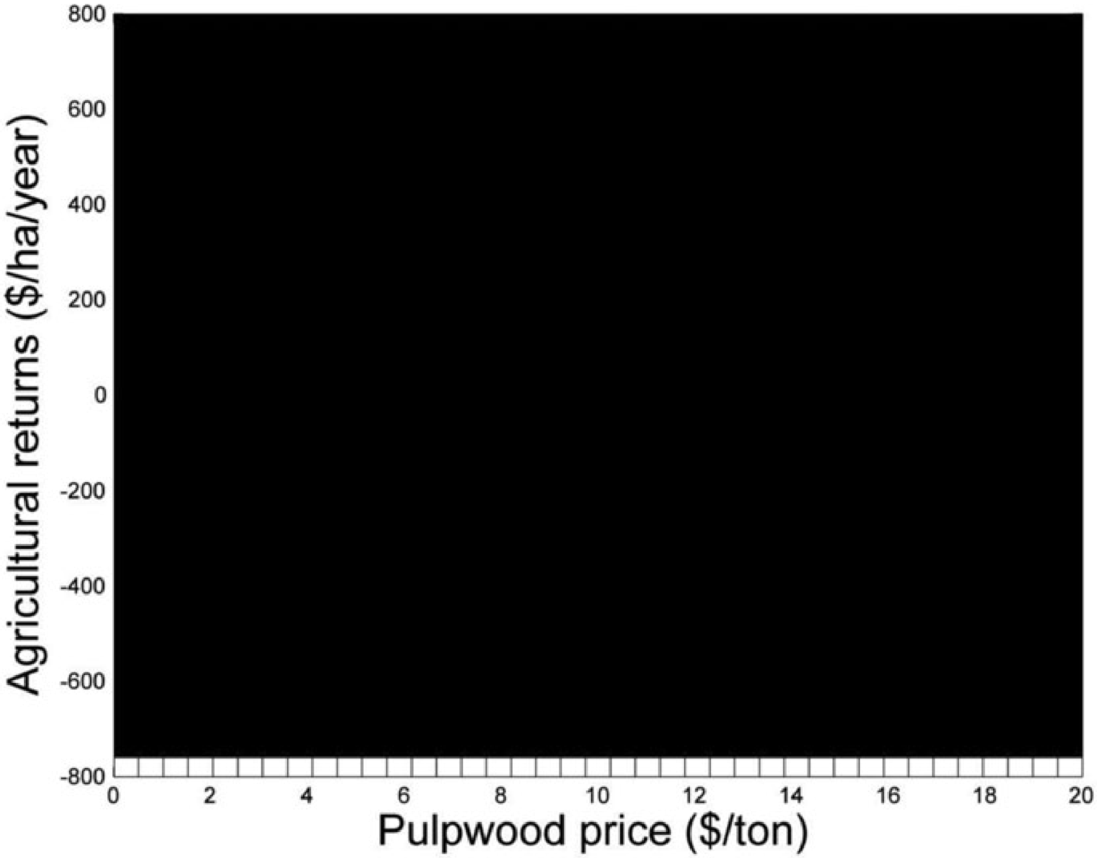
[4] We used prevailing units for timber and carbon markets in the US South, specifically US or short "tons" for timber, and metric "tonnes" for carbon.



Note: White cells represent switching to alley cropping, black cells represent staying in agriculture.

Fig. 2. Optimal decisions for RO model comparing agriculture to hard hardwood alley cropping, LCC 5 land, currently in agriculture ($s^{SA} = 0$).

summarized as the approximate level of agricultural returns per hectare below which a farmer/landowner would find it optimal to switch to alley cropping, regardless of timber price.

Fig. 3 shows a similar decision, but on land that has recently been planted to a hard hardwood alley cropping system. In this graph, the white cells represent maintaining the alley cropping system at least until next year, whereas the black cells represent clearing the planted trees and returning to agriculture. In this case, the level of agricultural returns above which a landowner reverts from the alley cropping system back to agriculture would be the "RO disadoption threshold." This disadoption threshold varied depending on the age of the stand. At this stand age, the disadoption decision was still primarily driven by agricultural returns rather than timber prices, but the level of agricultural returns at which one would revert to agriculture from agroforestry (disadoption threshold) was much higher than the level at which one would remain in agriculture for land in agriculture (adoption threshold).

Fig. 4 shows the optimal decisions for the hardwood alley cropping stand at stand age 10. When both agricultural returns and pulpwood price are high, it is optimal to capitalize on the high pulpwood value by clear-cutting, and then also capitalize on the likely continued high agricultural returns by switching back to agriculture for the future. However, at a stand age of 10 years, if either agricultural returns or timber are low, it is optimal to continue waiting.

From stand age 20 to 35 (not shown in figures), within the state space shown (timber price $0–20/ton, agricultural returns −$800–800/ha), there is no optimal decision other than allowing the agroforestry stand to continue. That is, the figures would show only white cells. After age 35, our growth and yield model began to show that some timber could be sold as sawtimber. Therefore, it is optimal for landowners to wait from age 20 to 35 in order to capitalize on selling sawtimber afterwards.

Fig. 5 represents optimal decisions for the same stand at age 49. The black cells represent harvesting the timber and clearing the stumps to return to agriculture, white represents keeping the forest stand at least one more year and gray represents harvesting the timber and replanting timber seedlings. At low levels of timber prices, it was optimal to wait, to see if the price would increase in the future, regardless of the value of agricultural returns. For this particular agroforestry system, as described in Table 1, the landowner would maintain the stand and conduct a small, sustainable harvest equal to the mean annual timber volume increment. For other systems, such as those involving cottonwood, which is generally managed as an

Note: White cells represent staying in alley cropping, black cells represent switching to agriculture.

Fig. 3. Optimal decisions for RO model comparing agriculture to hard hardwood alley cropping, LCC 5 land, recently planted to alley cropping ($s^{SA} = 1$).

even age stand, there would be no small, annual harvest, that is, the white cells represent the decision of "doing nothing," simply waiting to see how prices and returns evolve in the future.

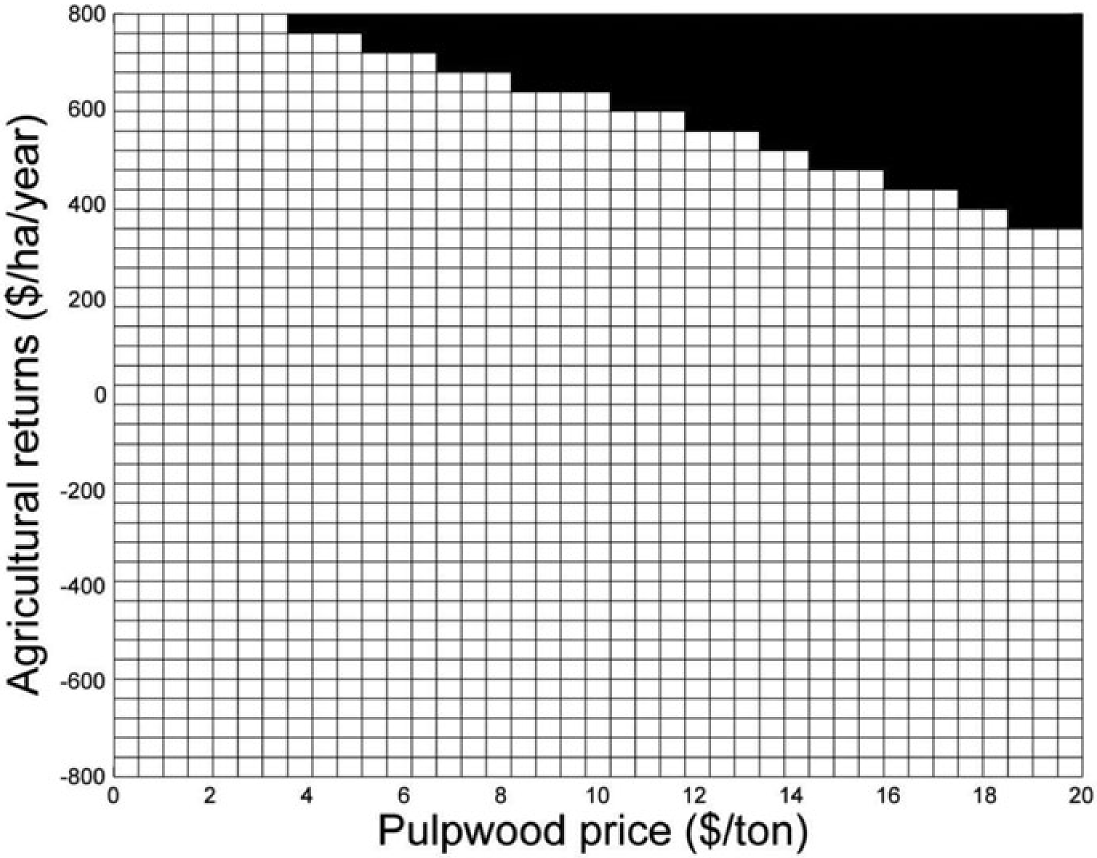
At higher timber and agricultural prices the landowner would clear-cut the forest to return to agriculture (black cells), and at high timber but lower agriculture returns he/she would clear-cut and replant the alley cropping system (gray cells). In Fig. 5, we see that the disadoption threshold does depend on the price of timber at this older stand age. At low values of timber prices, harvesting the timber (either to replant the trees or to convert to agriculture) is not optimal, because there is value in waiting until prices increase. This is true at any agricultural returns value within the state space. Therefore, the disadoption threshold at these lower values of timber prices, including at the equilibrium value of pulpwood of $5.90/ton, is greater than $800/ha; that is, if the timber price is at equilibrium, agricultural returns would need to be something greater than $800/ha for converting to agriculture to be optimal. However, at higher timber prices, the disadoption threshold is lower; that is, at a pulpwood price of $20/ton, if agricultural returns were above −$120/ha, then the optimal decision would be to harvest timber, clear stumps, and plant agricultural crops. Higher timber prices would lead to less forest, but only if agricultural returns are also high enough.

The disadoption threshold of agricultural returns at which the landowner would revert to agriculture after a clear-cut rather than replant the agroforestry system was much higher than the level at which he/she would stay in agriculture on a field that is already in agriculture (compare division between black/gray in Fig. 5 to division between black/white in Fig. 2). This was due to the fact that in order to revert to agriculture after agroforestry, he/she would have to invest in removing stumps.

5.2.3. *Adoption thresholds*

Similar figures can be drawn for all the forestry and agroforestry systems, at all stand ages. The adoption thresholds of production forestry and agroforestry systems on agricultural land are summarized in Table 3 for LCC 3 and Table 4 for LCC 5 land. Disadoption thresholds at the equilibrium timber price and at the maximum timber price are summarized in Table 5 for LCC 3 and Table 6 for LCC 5 land.

At first glance, the outlook may appear quite poor for most forestry and agroforestry activities in the LMAV as agricultural returns must become significantly negative for switching from agriculture to become optimal. However, this does not mean that



Note: White cells represent staying in alley cropping, black cells represent clear-cutting and switching to agriculture.

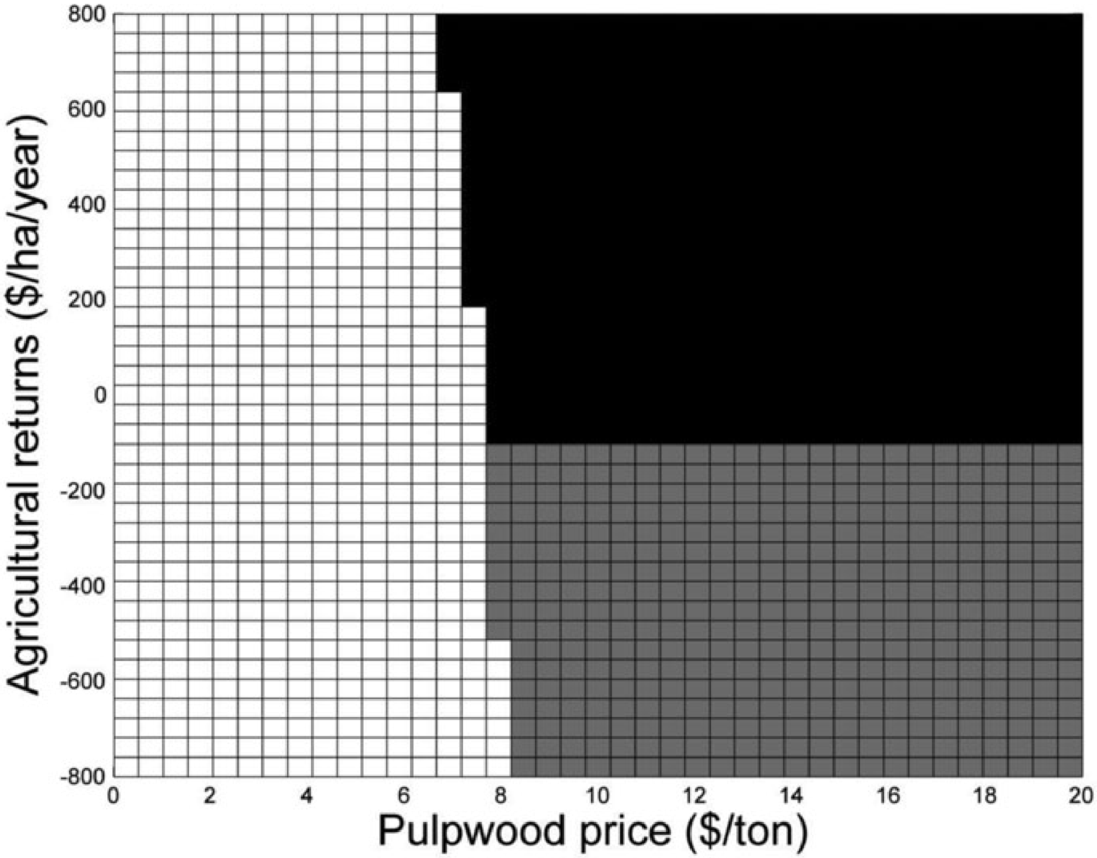
Fig. 4. Optimal decisions for RO model comparing agriculture to hard hardwood alley cropping, at stand age 10 ($s^{SA} = 11$).

agricultural returns must be negative over a long period; they only have to be that low one year for the farmer to decide it is worthwhile to plant trees. It seems reasonable that net returns on marginal LCC3 and LCC5 lands will occasionally be negative. On LCC 5 sites, three forestry and agroforestry systems have greater than a 5% chance of being adopted on any given plot in any given year. On LCC 3 sites, however, no system had a greater than one-in-a-thousand chance of being adopted in any given year.

The "RO value" in Tables 3 and 4 is the numerical value estimated for the value function, $V(s)$, assuming forestry/agroforestry at the year of site planting, at equilibrium prices, *ageq* and *timbeq*. This is comparable to the SEV in some cases, but allows for increased value from numerous options, including the option to switch back to agriculture. In fact, in many cases on recently planted forestry or agroforestry LCC 3 land, at equilibrium prices, the optimal decision is to switch back to agriculture immediately. In these cases, which are noted in the tables, it is not necessarily appropriate to compare the RO value to the SEV, because the RO model is essentially estimating the returns from an immediate return to agriculture, so the RO value represented is closer to the SEV of agriculture, not forestry or agroforestry.

Although SEV can be used to estimate returns and optimal timber rotation under numerous pricing regimes, SEV is a deterministic model that cannot place a value on flexibility under risk. That is, SEV does not include the option value created by flexibility in the face of changing timber prices. In every case, the RO value was higher than the SEV. This reflects the fact that flexibility under risk can only increase the value of a system, as well as the fact that the RO calculation includes the potential to have future annual revenues from agriculture. The systems with the RO value closest to SEV are those with the least flexibility. Most notably, this includes the WRP, which requires landowners keep plots forested into perpetuity. In the model, we did not include the possibility of breach of contract.

Annual equivalent value (AEV) is also included in the tables from Frey et al. (2010). The AEV can be viewed as the "SEV adoption threshold," the level of agricultural returns below which it is optimal to switch to the forestry or agroforestry system, utilizing SEV assumptions about discount rates, etc. In most cases, the RO analysis shows a more negative threshold of agricultural returns for switching to forestry or agroforestry than the SEV analysis. This means that the greater degree of flexibility associated with annual cropping means in most cases farmers would be less likely to adopt forestry or agroforestry



Notes: White cells represent staying with hardwood, black cells represent clear-cutting and switching to agriculture, gray cells represent clear-cutting and replanting alley cropping system. Note that sawtimber price is measured in exact proportion to pulpwood price. The price of hard hardwood sawtimber is 6.52 (product of parameters *pulpsaw* and *oakmixed*) times the pulpwood price.

Fig. 5. Optimal decisions for RO model comparing agriculture to hard hardwood alley cropping, land with 49-year-old or older stand ($s^{SA} = 50$).

than a simple SEV analysis might suggest. To be specific, on LCC 5 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, short-rotation woody crops, hard hardwood timber plantation, cottonwood–oak intercrop plantation, pecan alley cropping, and hardwood alley cropping. The RO adoption threshold was higher than the SEV adoption threshold for cottonwood timber plantation and cottonwood alley cropping. On LCC 3 land, all of the systems had substantially lower RO than SEV adoption thresholds.

Quantitatively, for the six systems on LCC 5 land that have lower RO adoption thresholds than for SEV, assuming a land clearing cost of $1,356/ha, the RO model finds a threshold that is on average approximately $550/ha lower than the SEV threshold, with differences ranging from approximately $830/ha (hard hardwoods alley crop) to $350/ha (WRP). This means that the agricultural returns at which it is optimal to switch to forestry/agroforestry is predicted by the RO model to be on average $550/ha lower in these cases than the SEV model.

Tables 3 and 4 also show the probability of crossing the RO adoption threshold in any given year based on the assumption of a normal distribution of agricultural returns. For all the systems on LCC 3 and for the poorest system on LCC 5 land (hard hardwoods and hard hardwoods alley crop), there is less than a 0.1% probability that it would be optimal to adopt those systems in any given year. Other systems are more favorable on LCC 5 land with probabilities of being optimal in any given year ranging from 0.3% (hard hardwoods) to 43% (cottonwood alley crop).

It is relatively easy to understand why the RO threshold is lower than the SEV threshold for WRP enrollment. In the RO model, we have assumed that once a plot of land is enrolled in WRP, it can never return to agriculture. Also, no timber harvest is permitted. The only income after the easement payment is income from a hunting lease. This means that WRP has essentially no flexibility. Still, it is important to note, that even with this lack of flexibility, the returns to WRP enrollment on LCC 5 land are high enough that it is a more attractive option in the RO model than many of the other forestry and agroforestry regimes. This intuitive because the positive cash flow from the easement payment comes sooner than the revenue from a lengthy rotation.

Of the forestry and agroforestry production systems, the most attractive in the RO model are cottonwood alley cropping and cottonwood plantation. Alley cropping systems have mixed

Table 3
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/year)

	RO adoption threshold ($/ha/year) Land clearing cost:		Prob. of crossing threshold* (%)	Annual equivalent value (SEV adoption threshold)	RO value, at land clearing cost $1356/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 4
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/year)

	RO adoption threshold ($/ha/year) Land clearing cost:		Prob. of crossing threshold* (%)	Annual equivalent value (SEV adoption threshold)	RO value, at land clearing cost $1,356/ha	SEV**
	$1,356/ha	$500/ha				
Wetlands Reserve Program	−240	−240	7	112	2,236	2,233
Cottonwood	140	140	55	61	3,770	1210
Short Rotation Woody Crop	−550	−550	0.3	−113	1,548	−2,253
Hard Hardwoods	−730	−690	<0.1	−6	955	−129
Cottonwood–Oak Intercrop	−510	−420	0.5	1	1,469	18
Pecan Alley Crop	−450	−450	0.9	−12	1,834	−235
Hard Hardwoods Alley Crop	−830	−600	<0.1	0	1,346	−8
Cottonwood Alley Crop	270	270	75	68	3,471	1,367

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

results relative to conventional forestry systems. Cottonwood alley cropping had a higher adoption threshold than conventional cottonwood, but hard hardwoods alley cropping was lower than conventional hard hardwoods, at least with the $1,356/ha land clearing cost assumption.

It is important to recall that this model assumes a fixed equilibrium value under mean reversion. That is, the expectation is that prices and returns will return to a fixed equilibrium over the long term. However, we know that occasionally market changes may cause equilibriums to shift. If the land manager believes equilibrium has become lower than in the past, his/her adoption thresholds will change. However, if he/she believes they will return to the equilibrium, the adoption thresholds will remain the same. Results of a shift in parameters (market shift) are discussed below.

5.2.4. *Disadoption thresholds*

The opposite of the adoption threshold is the disadoption threshold; it is the level of agricultural returns above which a land manager would optimally decide to harvest available timber, clear the land of stumps, and switch to agricultural crops. The disadoption threshold varies depending on the age of the stand and the value of the timber price, as seen in Figs. 3–5, and explained above.

Tables 5 and 6 show the disadoption thresholds at increasing stand ages at the equilibrium timber price and at the maximum timber price. At most stand ages, the disadoption threshold is lower at the maximum timber value than at the equilibrium timber price. This is seemingly a paradox, as one would think that a higher timber price would more likely convince the land manager to stay in forestry. However, the reason is clear in Fig. 5. At lower timber prices, it is generally optimal to simply wait for the price to improve. Once the timber price is high enough, if agriculture returns are low the manager will harvest and replant trees, but if agricultural returns are high he/she will harvest the timber and convert to agriculture.

However, at low stand ages, in some cases this trend is reversed; the disadoption threshold is lower at the equilibrium timber price than at the maximum timber price. This is because

Table 5
Real options disadoption thresholds for production forestry and agroforestry systems on land capability class (LCC) 3 land ($/ha/year) at various stage ages; Land clearing cost = $1,356/ha

	RO disadoption threshold ($/ha/year) Stand age:					
	1	2	5	10	20	Max. age in model
Wetlands Reserve Program*						
At equilibrium timber price	800	800	800	800	800	800
At maximum timber price	800	800	800	800	800	800
Cottonwood						
At equilibrium timber price	200	360	750	800	800	800
At maximum timber price	200	390	130	690	−420	−420
Short Rotation Woody Crop						
At equilibrium timber price	−30	0	−160	NA	NA	−160
At maximum timber price	260	−100	−800	NA	NA	−800
Hard Hardwoods						
At equilibrium timber price	0	40	80	120	330	800
At maximum timber price	0	40	−200	−660	−700	−700
Cottonwood–Oak Intercrop						
At equilibrium timber price	0	0	370	800	210	800
At maximum timber price	0	120	−370	800	−660	−660
Pecan Alley Crop						
At equilibrium timber price	−800	−40	800	800	800	800
At maximum timber price	−800	−40	800	800	800	800
Hard Hardwoods Alley Crop						
At equilibrium timber price	−120	−80	−80	40	80	800
At maximum timber price	−120	−40	−330	−490	−490	−490
Cottonwood Alley Crop						
At equilibrium timber price	30	160	520	800	800	800
At maximum timber price	30	200	200	780	−800	−800

Table 6
Real options disadoption thresholds for production forestry and agroforestry systems on land capability class (LCC) 5 land ($/ha/year) at various stage ages; Land clearing cost = $1,356/ha

	RO disadoption threshold ($/ha/year) Stand age:					
	1	2	5	10	20	Max. age in model
Wetlands Reserve Program						
At equilibrium timber price	800	800	800	800	800	800
At maximum timber price	800	800	800	800	800	800
Cottonwood						
At equilibrium timber price	800	800	800	800	800	800
At maximum timber price	800	800	800	800	800	800
Short Rotation Woody Crop						
At equilibrium timber price	290	290	70	NA	NA	70
At maximum timber price	520	100	−620	NA	NA	−620
Hard Hardwoods						
At equilibrium timber price	660	700	800	800	800	800
At maximum timber price	660	740	580	450	660	160
Cottonwood–Oak Intercrop						
At equilibrium timber price	800	800	800	800	800	800
At maximum timber price	800	800	370	800	370	330
Pecan Alley Crop						
At equilibrium timber price	800	800	800	800	800	800
At maximum timber price	800	800	800	800	800	800
Hard Hardwoods Alley Crop						
At equilibrium timber price	290	330	490	780	800	800
At maximum timber price	290	330	210	330	700	−120
Cottonwood Alley Crop						
At equilibrium timber price	800	800	800	800	800	800
At maximum timber price	800	800	800	800	800	800

at these low stand ages the timber has essentially no value in the present.

It is also important to note that the disadoption thresholds tend to be significantly higher than the adoption thresholds. This means that once a land manager switches into forestry/agroforestry, he/she is less likely to switch back to agriculture than to simply stay in agriculture when he/she is already in agriculture. This is consistent with what we know about option value, given that there are financial barriers to switching between land uses.

Interestingly, the systems with the highest adoption thresholds (most likely to be adopted) are not the same as the systems with the highest disadoption thresholds (least likely to be disadopted). This means that some systems, such as cottonwood and cottonwood alley cropping, which have relatively high adoption thresholds and low disadoption thresholds, are more likely to go back and forth with agricultural land uses. On the other hand, some systems such as pecan alley cropping, are unlikely to be adopted, but once adopted, are unlikely to be disadopted. These tend to be the systems with a higher up-front cost, but higher income in the long term.

5.2.5. *Sensitivity analysis with lower land clearing cost*

Because of the high variability of estimates of the land clearing cost, we ran the same models with a lower clearing cost ($500/ha instead of $1,356/ha) to test its affect on the results. The affect on the adoption threshold is shown in Tables 3 and 4. In many cases, the change in the adoption threshold was within the range of precision of the model; that is, with the low resolution of the model, we could not detect a change. In the systems for which we could detect a change in the adoption threshold, a reduction in land clearing cost unambiguously, although only slightly, raised the adoption threshold, meaning forestry or agroforestry would be easier to adopt if land clearing costs are lower.

Lowering the land clearing cost had the opposite effect on the disadoption threshold (not shown). The disadoption threshold was unambiguously lower at a lower land clearing cost, meaning it is easier to shift from forestry/agroforestry to agriculture. The change was somewhat larger in magnitude than for the adoption threshold.

These two results are entirely consistent with option value. Land clearing costs are a barrier to switching. When these costs are reduced, it becomes easier to switch between land uses, in either direction. The ultimate effect is to reduce the distance between the adoption and disadoption thresholds.

5.3. *Market shifts and policy programs*

We utilized the alternative scenarios 1–3 described earlier to simulate the effect of various potential market shifts on adoption and disadoption of forestry on LCC 3 land (see results in Table 7). None of the alternative scenarios affected WRP greatly, because it was modeled as a program without much flexibility in terms of unenrolling.

Table 7
Adoption and disadoption thresholds ($/ha/year) for alternative scenarios 1–4

	Adoption threshold	Disadoption threshold, age 10	Disadoption threshold, max stand age
Wetlands Reserve Program base	−1, 000	800	800
Scenario 1	−1, 000	800	800
Scenario 2	−1, 000	800	800
Scenario 3	−1, 000	800	800
Scenario 4	−1, 000	800	800
Cottonwood base	−1, 000	690	−420
Scenario 1	−100	800	780
Scenario 2	−120	800	750
Scenario 3	−290	800	690
Scenario 4	−80	800	800
Short Rotation Woody Crop base	−980	NA	−800
Scenario 1	−810	NA	−800
Scenario 2	−810	NA	−800
Scenario 3	−780	NA	−800
Scenario 4	−980	NA	420
Hard Hardwoods base	−1, 000	−660	−700
Scenario 1	−1, 000	−210	−620
Scenario 2	−1, 000	−210	−620
Scenario 3	−1, 000	−160	−530
Scenario 4	−1, 000	800	800
Cottonwood–Oak Intercrop base	−1, 000	800	−660
Scenario 1	−1, 000	800	−210
Scenario 2	−1, 000	800	−210
Scenario 3	−1, 000	800	−160
Scenario 4	−1, 000	800	800
Pecan Alley Crop base	−1, 000	800	800
Scenario 1	−1, 000	800	800
Scenario 2	−1, 000	800	800
Scenario 3	−1, 000	800	800
Scenario 4	−1, 000	800	800
Hard Hardwoods Alley Crop base	−1, 000	−490	−490
Scenario 1	−1, 000	−250	−490
Scenario 2	−1, 000	−250	−490
Scenario 3	−1, 000	−120	−410
Scenario 4	−980	800	800
Cottonwood Alley Crop base	−1, 000	780	−800
Scenario 1	20	800	690
Scenario 2	0	800	690
Scenario 3	−140	800	560
Scenario 4	230	800	800

In comparing the alternative scenarios, there was very little difference in the effect of Scenario 1 (double in timber equilibrium prices) and Scenario 2 (double in timber equilibrium prices and 50% decrease in timber price volatility). The decrease in timber volatility therefore seemed to have little effect on the outcome. In alternative scenarios 1 and 2, an increase in equilibrium timber price did not significantly affect the low adoption thresholds of hard hardwood and nut systems (hard hardwoods, cottonwood–oak intercrop, pecan alley crop, hard hardwoods alley crop) on LCC 3 land. All were still below a 0.1% probability of crossing the threshold in any given year. However, primarily cottonwood/soft hardwood systems (cottonwood, cottonwood alley crop, and to a lesser extent short-rotation woody crops) were affected to a much greater extent. This is may be indicative of the fact that cottonwood systems can take advantage of higher pulpwood prices faster through a pulpwood harvest. In this sense, it is surprising that the short-rotation woody crop model did not perform as much better as the other cottonwood systems.

Scenario 3 (double in timber equilibrium prices and 50% increase in agricultural returns volatility) changes in adoption and disadoption thresholds relative to the base case were generally in the same direction as Scenarios 1 and 2, but somewhat smaller in magnitude. This indicates that the increase in agricultural returns volatility actually had a mitigating effect. More variable agriculture actually favors agriculture.

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, the disadoption threshold relative to the base case, meaning forestry and agroforestry would be less likely to be disadopted.

Scenario 4 (Table 7) reflected a world with potential conflicting policies: Farm bill payments based on existing policies, which favor agriculture, and possible future market-based payments for carbon and nitrogen, which favor forests. 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 does include 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 added, forests are more strongly favored than the base case, indicating that these payments could more than counteract farm bill agricultural payments. In fact, these payments have a stronger effect relative to the base case than a doubling of timber price, as in Scenario 2.

6. Conclusions

Previous literature has found that option value can play an important role in land use decisions, demonstrating that flexibility in deciding when to harvest can add significant value to timberlands (Haight and Holmes, 1991; Plantinga, 1998), and that the option value of agriculture is likely to cause farmers to delay reforestation (Behan et al., 2006; Weimers and Behan, 2004). We utilized an RO model to examine the adoption potential and disadoption risk of agroforestry and production forestry in the LMAV and compare to deterministic models. We combine both decisions into one model to include both the option value of agriculture and forestry. Our results confirmed that, in most cases, option value favors agriculture, meaning that farmers will be more hesitant to adopt forestry and agroforestry than is suggested by the purely deterministic model.

There are some limitations to our approach. While including risk in the model more accurately reflects the world that real land managers face, some assumptions must be made to make the problem tractable. First, we had to limit the number of state variables. This included, for instance, assuming that the sawtimber and pulpwood prices always maintained the same relative values (that is, sawtimber price per ton is always exactly x times the pulpwood price). This allowed combining the two variables into one, but ignores cases where the two prices might change differently over time. Second, we created a simple stochastic Ornstein–Uhlenbeck model of how agricultural returns and timber prices evolve over time. Although this model was based on historical data, it may or may not accurately reflect the future risk scenarios that land managers face. Third, while the agricultural returns and timber prices some of the other costs and revenues were assumed to be fixed. The assumed magnitude of these parameters could have an impact on some of the results. We did undertake sensitivity analyses on some of the most important of these parameters, including the cost of clearing land, to test how changes in the parameters affect the results of the model. Fourth, this model is specific to the LMAV, and the soils and markets found there.

The RO model produced some notable results. On the most marginal land, two systems—cottonwood and cottonwood alley cropping—showed more adoption potential than the WRP program. Since we know that the WRP has been adopted by many landowners—totaling over 275,000 ha by 2005 (King et al., 2006), this may be an indicator of potential for adoption of those other systems. On the other hand, anecdotal evidence and the notes of the Delphi panelists indicate that many landowners may adopt WRP because it is a good way to get out of farming altogether, which is a nonmarket value that cannot be modeled in RO, and could make WRP more favorable than agroforestry. On average-quality LMAV land, none of the forestry or agroforestry systems showed potential.

The RO model showed that the option value provided by agriculture outweighs the option value provided by forestry and agroforestry systems, making adoption of forestry and agroforestry less favorable than estimated by deterministic models. However, once adopted, most of the systems had fairly high disadoption thresholds; that is, they were less likely to be disadopted.

We assumed normality in the distribution of agricultural and forestry net returns. Certainly, the magnitude of the changes in the adoption threshold relative to the deterministic model would be sensitive to changes in the distribution of returns. However, based on our work with the underlying models, we are confident that the direction of the change relative to the deterministic model would be fairly robust to changes in the distribution. That is, even if agricultural and forestry net returns are not normal, if their relative variances are similar to what we have estimated, more option value is derived from agriculture than forestry or agroforestry, making them less attractive than capital budgeting models predict.

Policy impacts forestry and agroforestry adoption and disadoption. Our base results above indicate a more pessimistic outlook for forestry and agroforestry adoption for simple financial returns than a simple capital budgeting model would indicate. That is to say, left to agricultural and timber markets, unless there is a shift in equilibrium prices, LCC 3 and 5 lands in the LMAV are likely to remain in agriculture. However, if carbon and nitrogen markets emerge, then there is strong potential for forest-based systems on these lands.

We do not see much potential for adoption of agroforestry in large areas or on land that is not marginal for farmers whose principal goal is profit maximization. There was some evidence that agroforestry might be easier to adopt than conventional forestry, but the difference is only slight. Even on marginal private land, WRP is likely to continue to be the principal reforestation program in the LMAV. However, there may still be some small potential for adoption on marginal lands in the LMAV for farmers or landowners who want to practice stewardship or sustainable practices but who do not want to commit to a permanent easement through WRP. These are most likely to be limited-resource farmers or landowners for whom farming is more of a lifestyle than an occupation. Various subsidy programs or other payments for environmental services also could make agroforestry or forestry adoption more likely, essentially paying the difference to convert from the agriculture practices to the forest conservation practices.

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