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Under what management and policy scenarios can alley cropping be a competitive alternative in the United States Southeast?

Gregory E. Frey · Michael A. Cary

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Abstract Despite statements that it can mitigate financial risk through farm diversification, alley cropping in the United States Southeast has not been comprehensively modeled to estimate potential financial returns and risks. We used a Monte Carlo method to model stochastic financial returns to monocropping agriculture, loblolly pine plantation, and loblolly pine alley cropping in North Carolina, USA, plotting the results from 25,000 iterations to understand financial risk. Under certain scenarios and assumptions, alley cropping did have financial returns comparable to, or potentially higher than, monocropping agriculture, but did not lower overall risk, as measured by the spread of the distribution of financial returns. Pine plantations, on the other hand, did have lower risk than both alley cropping and monocropping. Alley cropping with wider 24.4-m alleys performed better than narrow 12.2-m alleys. Allowing the producer to choose a timber rotation length that optimizes financial returns generated the best financial returns for alley cropping, but this assumes perfect knowledge of the manager and is unrealistic. Current policy programs of government payments for commodity crops and cost-share for tree planting, tend to favor monocropping over alley cropping or pine plantation. A hypothetical system of payments for carbon sequestration does increase pine plantation and alley cropping financial returns, but not to the extent that commodity crop programs currently increase monocropping financial returns, and does not reduce risk significantly. Overall, on average agricultural land in North Carolina, alley cropping may be of value to certain producers, but we find those possibilities to be somewhat limited.

Keywords Agroforestry · Forestry · Monte Carlo · Stochastic modelling · Risk · Policy

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G. E. Frey (✉)
Southern Research Station, USDA Forest Service, 3041 E. Cornwallis Rd., Research Triangle Park, NC 27709, USA
e-mail: gregory.e.frey@usda.gov

M. A. Cary
Division of Resource Economics and Management, West Virginia University, Morgantown, WV, USA

Introduction

Agroforestry, which combines trees with crops or livestock, has been suggested as a potential method of mitigating environmental impacts of agriculture (Dosskey et al. 2012), while generating competitive financial returns at lower risk (MacFarland 2017; Wolz and DeLucia 2019). Alley cropping is an agroforestry system wherein rows of woody perennials (the tree component), separate wider alleys of crops (the crop component) (Wolz and DeLucia 2018). Alley cropping is one of the least researched and practiced types of agroforestry systems in the United States Southeast (Workman et al. 2003). Still, it has been suggested that alley cropping systems have potential for higher overall yield and lower risk than monocultures (Haile et al. 2016; MacFarland 2017). This research concerns itself with that proposition.

Agroforestry financial estimates, based on deterministic cash flow capital budgeting, have ranged from poor to potentially competitive with conventional monocropping agriculture on certain soil types (Cubbage et al. 2012; Frey et al. 2010; Susaeta et al. 2012; Wolz and DeLucia 2019). These are an important starting point, yet do not include stochastic processes that drive financial risk. Financial risk may be an important consideration in system adoption and land use management; indeed, one of the main purported benefits of alley cropping is product diversification, which is assumed to be desirable because it can provide financial risk mitigation (MacFarland 2017; Workman et al. 2003). Alley cropping may also allow practitioners to change annual crops from year to year and change timber harvest timing, in response to market or growth conditions (Nana and Lu 2013).

Research on financial risk of integrated agroforestry systems compared to monocropping alternatives is extremely sparse, due to the diversity of system types, relatively short period of existing research plots, and data-intensive needs of risk modeling (Blandon 2004). Research on agroforestry in the tropics is more common than temperate regions. In the tropics, some financial risk research has found a trade-off between financial returns and risk, with agroforestry offering lower risk, but also lower returns than monocropping (Reeves and Lilieholm 1993; Djanibekov and Villamor 2017). Other studies have assumed beneficial tree-crop interactions such as reduced heat stress on annual crops in an alley cropping microclimate or improved nutrient cycling, and found various agroforestry systems could generate both higher financial returns and lower risk than monocropping (Paul et al. 2017; Ramirez et al. 2001; Santos Martin and van Noordwijk 2009). Limited research on agroforestry in temperate regions of Europe and Asia suggest a stricter trade-off between risk and returns with agroforestry potentially appealing to only to highly risk-averse producers (Blandon 2004; Djanibekov and Khamzina 2016). We are aware of no previous research that comprehensively models and explores the financial returns and risks and management choices of temperate North American alley cropping and alternate land uses.

The objective of this research was to compare the potential financial return distributions of alley cropping with traditional monocropping agriculture and plantation forestry in the U.S. Southeast. We utilized a Monte-Carlo simulation to account for decision points and most potential sources of price and yield risk. We examined the effect of potential management and policy choices on financial returns and risks.

Data and methods

We focused on the upper coastal plain region of North Carolina and Virginia, USA, which has strong forestry and agricultural sectors, but has received little attention for alley cropping in the past. However, there is increasing interest among researchers, who have recently established alley cropping demonstration sites (Cubbage et al. 2012; Pollock 2012), and anecdotally among a subset of producers. We selected Halifax County, NC because it has average to high production of numerous commodity crops among counties in North Carolina, has numerous small and medium-sized farms, and minority-owned farms (NASS 2019).

We utilized the Agroforestry Land-use Economic Yield and Risk (ALLEY) Model, version 2.0.1, in MATLAB to simulate financial returns.[1] The basic

[1] Detailed methods on the ALLEY 2.0.1 are described in Frey et al. (2018) and the code and data described are available for download at https://www.srs.fs.usda.gov/pubs/gtr/gtr_srs235/.

ALLEY 2.0.1 was created and run in MATLAB version 2015b with Statistical Toolbox but should be compatible with other versions of MATLAB as well as open-source software such as GNU Octave. MATLAB is commercial software and its approach of ALLEY 2.0.1 is briefly described here, but more detail can be found in Frey et al. (2018). We modeled an alley cropping system consisting of a perennial timber tree and annual crops. These are the predominant types of tree and crop components in temperate alley cropping systems (Wolz and DeLucia 2018).

Crop component

Annual commodity crops are the most commonly researched crops for alley cropping in the Southeast, followed by perennial forage and biomass crops such as switchgrass (Blazier et al. 2012; Haile et al. 2016; Miller and Pallardy 2001; Wanvestraut et al. 2004; Wolz and DeLucia 2018; Zamora et al. 2008, 2009). However, Workman et al. (2003) found that specialty crops including fruits, vegetables, and cut flowers are more common on working alley cropping farms observed in the Southeast.

We chose three common commodity crops: corn (*Zea mays*), soybeans (*Glycine max*), and cotton (*Gossypium hirsutum*). Historical data for yields and prices for each commodity were obtained at the smallest geographic level possible: average output price in North Carolina (NASS 2016), yield in Halifax County (NASS 2016), and input cost for the Southeast/Southern Seaboard region (ERS 2016).[2] The mean and standard deviations for 1976–2015 are given in Table 1. Cotton posed a modeling challenge, as two outputs are marketed: lint and cottonseed. We found an "imputed price of cotton lint" by dividing the total revenue of both products by the yield of cotton lint.

The commodity crops were assumed to have highest production when trees are small and competition is less, and decline in yield as competition with trees increased. The yield response is non-linear, with only a small decline when trees are small, but declining more rapidly when trees are larger (Frey et al. 2018).[3] Additionally, we constructed financial profiles for two hypothetical "specialty" crops, which are not based on historical data. Specialty crops are those which have local and/or limited markets, and therefore have little historical data available. The inclusion of hypothetical specialty crops permits us to examine what financial properties of a potential alternative to commodity crops would be successful (scenario 4, "Specialty crops" section below). Assumed values were largely based on the average parameter values of the commodity crops, with small alterations (Table 2, and Appendix 2, Supplemental Tables S1–S2). These alterations ensured the specialty crops have relatively low annual profits compared to the commodity crops, but characteristics that might make them useful in certain situations. Specialty crop 1 was assumed to be a crop more adapted to alley cropping and had relatively higher yield when there is a microclimate such as with moderate-size trees, perhaps due to lower moisture stress and heat stress (competition profile 2).[3] Specialty crop 2 had a competition profile like commodity crops,[3] but had countercyclical covariance (intercrop correlation profile -1), meaning that it may have a profitable year

Footnote 1 continued
use in this model does not imply endorsement by the authors or their institutions.

[2] We included all production input costs except the opportunity costs of unpaid labor and land. In general, this included the following cost categories: Seed; Fertilizer, lime, and gypsum; Chemicals; Custom operations; Fuel, lube, and electricity; Repairs; Hired labor; Purchased irrigation water; Interest; Taxes and insurance; General farm overhead; Capital recovery of machinery and equipment.

[3] Competition profile refers to crop's response to competition with trees, where 1 indicates a crop that prefers full sun and 2 indicates a crop that thrives the microclimate of an alley with moderate-size trees (Frey et al. 2018, p. 26). In these competition profiles, expected crop yield is modeled as a non-linear function of the length of live crown of the trees; that is, more and larger trees with bigger crowns leads to more competition with the annual crop. The length of live crown (m/ha) is estimated at the plot level and is appropriate because if factors in both the size of the trees, the overall number of trees per hectare, and the density of trees within the tree rows. With regards to this latter point, we note that trees that are spread evenly over the plot will exert less competition among trees themselves, leading to larger crowns and more competition with the annual crop below. A similar number of trees per hectare, tightly packed in tree rows will exert more competition among the trees themselves, leading to smaller crowns and less competition with the annual crops.

Competition profile 1 declines slowly at first, then increases rapidly as trees get larger. Competition profile 2 increases slightly at first until trees reach a moderate size, then declines as trees get larger. Commodity crops were assigned competition profile 1, which is consistent with biological research which suggests that crop yields can be reduced by 25–50% due to competition with trees aged 5-10 years (Gillespie et al. 2000; Miller and Pallardy 2001; Wanvestraut et al. 2004; Zamora et al. 2009), assuming no additional management to limit this competition (root barriers or pruning, etc.).

Table 1 Mean and standard deviation crop output prices, yield, and input costs, 1975-2015, in real 2013 dollars

	Corn	Soybeans	Cotton[a]	Pine sawtimber	Pine pulpwood
Mean output price (\$/t for crops, \$/m^3 for timber)	214.9	456.1	2507.2	57.3	11.1
SD	(87.2)	(197.2)	(1039.3)	(14.3)	(1.4)
Mean yield (t/ha)	4.46	1.77	0.72		
SD	(1.07)	(0.37)	(0.22)		
Mean input costs (\$/ha)	1107.9	686.1	1989.2		
SD	(240.5)	(158.7)	(460.8)		

[a]Cotton yield information is for cotton lint, and the output price is an imputed price including the value of cotton lint and cottonseed/t of lint

Table 2 Key parameters for construction of commodity (corn, soybeans, cotton) and hypothetical specialty crops (SC1 and SC2). Other detailed parameters given in tables S1-S2

	Corn	Soybeans	Cotton	SC1	SC2
Competition profile[3]	1	1	1	2	1
Inter-crop correlation profile[4]	E	E	E	1	− 1

E Estimated from historical data (E) for commodity crops

when most other crops do poorly.[4] Such hypothetical countercyclical crops have been discussed in agroforestry literature as providing the most potential for risk mitigation and agroforestry adoption (Blandon 2004; Lilieholm and Reeves 1991), but experience suggests it is challenging to find a crop that thrives when most others fail, such as a drought or flood.

Tree component

The commercial timber species in the Southeast with most available data regarding growth, yield, and timber price is loblolly pine (*Pinus taeda*). Although not as commonly used as some hardwood tree species (Wolz and DeLucia 2018), loblolly pine has been used in experimental alley cropping systems (Blazier et al. 2012; Cubbage et al. 2012; Zamora et al. 2009).

Southern pine pulpwood and sawtimber stumpage prices for eastern North Carolina from 1976–2015 were obtained from NCCE (2014). Pine input costs include establishment, competition control, and annual management costs. We assume these costs to be strongly positively correlated in order to model a single stochastic pine input cost index variable of average 1. The cost index is necessary to limit the number of modeled variables in the multivariate simulation, to maintain computational feasibility, and was derived by summing the historical costs (Dooley and Barlow 2013) in each year and normalized by dividing by the average of those costs for all years. This index is then multiplied by a fixed value for the activity that is scheduled to occur in a given year, based on NCFS (2014) forest management cost estimates for Halifax County's district (D5-Rocky Mount).

Parameter estimation

All historical prices were adjusted to real 2013 dollars using the Consumer Price Index (CPI) (US BLS 2015). Using the historical data, we estimated a historical joint distribution of yearly shocks to all crops' three financial "returns elements": output price, yield, and

[4] Inter-crop correlation refers to the correlation between shocks to yield, price, and cost among the various crops, and were estimated from historical data for commodity crops. For specialty crops, 1 indicates a hypothetical direct correlation, and -1 countercyclical.

Table 3 Assumptions about autoregrssion-trend functional form and distribution of the shock for crop price, crop yield, crop input cost, timber price, and timber input cost

	Function number[a]	Function description	Equation[b]
Autoregression-trend functions			
Crop price	6	Decreasing exponential time trend, AR1 autoregression	$y_t = \beta_1 + \beta_2 \cdot e^{\beta_3 \cdot t} + \beta_4 \cdot y_{t-1} + \varepsilon_t$
Crop yield	5	Increasing exponential time trend, AR1 autoregression	$y_t = \beta_1 - e^{\beta_2 \cdot t} + \beta_3 \cdot y_{t-1} + \varepsilon_t$
Crop input cost	2	No time trend, AR1 autoregression	$y_t = \beta_1 + \beta_2 \cdot y_{t-1} + \varepsilon_t$
Timber price	2	No time trend, AR1 autoregression	$y_t = \beta_1 + \beta_2 \cdot y_{t-1} + \varepsilon_t$
Timber input cost index	0	Full mean reversion plus shock	$y_t = \bar{y} + \varepsilon_t$
Distribution functions			
Crop price	1	Lognormal distribution	$g \sim LN(c_1, c_2)$ $\varepsilon = g + minad$
Crop yield	2	Beta distribution	$g \sim Beta(c_1, c_2)$ $\varepsilon = g \cdot (maxad - minad) + minad$
Crop input cost	0	Normal distribution	$\varepsilon \sim N(0, c_1)$
Timber price	1	Lognormal distribution	$g \sim LN(c_1, c_2)$ $\varepsilon = g + minad$
Timber input cost index	0	Normal distribution	$\varepsilon \sim N(0, c_1)$

[a]As described and categorized in Frey et al. (2018)

[b]ε represents a randomly generated shock. *LN* represents the lognormal distribution, *N* the normal distribution, and *Beta* the beta distribution

input cost. Then, the simulation uses random draws from the estimated joint distribution (Frey et al. 2018).

Parameters were estimated by fitting a regression of the assumed autoregression-trend functional form given in Table 3 to the historical data. Estimated coefficients for autoregression-trend functions are output into matrix *S* (Appendix 2, Supplemental Table S1). The resulting residuals, or shocks, ε_t, were translated to a standard normal distribution based on the assumed distribution in Table 1. Estimated parameters for shock distribution functions are output by ALLEY 2.0.1 into a matrix called *D* (Appendix 2, Supplemental Table S2). We estimated a covariance matrix (*sigma*) of the normalized residuals (Appendix 2, Supplemental Table S3).

Monte-Carlo simulation

ALLEY 2.0.1 uses a Gaussian copula (Frees and Valdez 1998) to model all financial returns elements (output price, yield, input cost) for all crops. *D* and *sigma* together define the joint distribution of the shocks, and *S* translates those shocks into actual values of the financial returns elements. This creates a correlated joint distribution of the financial returns elements.[5]

[5] As in Frey et al. (2018), the one exception to this Guassian copula modeling is timber yield, which was modeled independently based on a growth and yield model, found in Westfall et al. (2004) and in Burkhart et al. (2008). ALLEY 2.0.1 also includes forest catastrophes (fire, pests, etc.), which are assumed to occur with probability 0.01, and kill a random proportion of trees from a normal distribution with mean 0.15 and standard deviation 0.15.

Comparison of financial returns and risk

Three land-use systems were modeled independently: monocropping, alley cropping, and loblolly pine plantation. The financial returns elements were simulated over a 40-year time horizon (*m*) with 25,000 replications (*n*), to determine average and distribution of long-run profits. We calculated the financial profit indicators net present value (NPV), soil expectation value (SEV), and annual equivalent income (AEI), using a 5% discount rate (Mercer et al. 2014). We also calculated the average optimal timber rotation,[6] number of years each crop was selected, and average government payment.

We utilize the concepts of first- and second-order stochastic dominance (Hadar and Russell 1969) to compare distributions of financial returns. Roughly speaking, first-order stochastic dominance means that one distribution has higher value (the x-axis in a cumulative distribution function) at any given quantile (the y-axis). That is, the dominant cumulative distribution function (CDF) is always to the right of the dominated one. *Any* producer should prefer a distribution that is first-order dominant.[7] Second-order stochastic dominance roughly means that one distribution has a mean at least as high as the other, and lower standard deviation (less risky). Any *risk-averse* producer should prefer a distribution that is second-order dominant.

Management scenarios

Base case

The base case is the simplest test case for comparing monocropping, alley cropping, and traditional loblolly pine plantation (Frey et al. 2018). To summarize, loblolly pine site index was 22.9 m (75 ft) at 25 years, a fairly good site for timber production. In the pine plantation model, trees were spaced at 2.44 × 3.05 m (8 × 10 ft), 1345 trees/ha (545 trees/acre). In the alley cropping model, the trees were spaced 2.44 × 2.44 m (8 × 8 ft) within double tree rows (Frey et al. 2018). The alley between double tree rows was 12.2 m (40 ft), which is intermediate between alley widths described in the literature (Blazier et al. 2012; Cubbage et al. 2012; Zamora et al. 2009), 560 trees/ha (227 trees/acre) overall.

We included the assumption of interspecific competition which reduced the yield of the alley crops as tree size increased. This competition profile 1 assumption for commodity crops would be consistent with little or no additional management of the trees to limit the competition effects, such as installing underground barriers to limit tree root growth into the alley (Zamora et al. 2008).

The base case assumed a fixed, 40-year timber rotation for the loblolly pine plantation and alley cropping, which is different than the standard ALLEY 2.0.1 assumptions (code modifications described in Appendix 1). This is more comparable to the monocropping model, since the monocropping model uses a 40-year time horizon (Frey et al. 2018).

Optimal rotation

The timber rotation calculated in standard ALLEY 2.0.1 chooses the timber rotation ex-post, based on whichever year generates the highest total timber and alley cropping SEV. This SEV-maximizing rotation is called the "optimal rotation." Since this allows more flexibility than a fixed rotation, financial returns should always be higher than the base case, and is indicative of the benefit of flexibility in changing timber rotations as market conditions (for both timber and crops) change. However, the optimal rotation as calculated in ALLEY 2.0.1 is unrealistic, as it assumes perfect knowledge of the past, present, and future market conditions. We include it as a best case scenario for loblolly pine and alley cropping.

Alley width

The base case assumed an alley cropping alley width of 12.2 m with 560 trees/ha. An alternative management choice was to use an alley width of 24.4 m (80 ft) for the annual crop area, leading to 305 trees/ha (124 trees/acre) overall. The 24.4 m alley was used in subsequent scenarios 4–6.

[6] The rotation that yields maximum SEV.

[7] Assuming that there are no other preferences that are not included in the estimate of profits, such as environmental stewardship).

Specialty crops

We constructed two hypothetical specialty crops (see "Crop component" section) to understand what financial profile of alternative, non-commodity crops will improve financial returns and risk in monocropping and alley cropping systems.

Policy scenarios

Commodity and cost share payments

Financial returns and risk can be altered by government incentives and support programs. We modeled the impact of two typical programs, one for agriculture and one forestry. The first is the Agricultural Risk Coverage–Individual Coverage (ARC–IC) program, authorized in the 2014 and 2018 Farm Bills (FSA 2014). Under this program, a payment is made if the revenue generated from a producer's crop is less than the "guarantee"—86% of the producer's benchmark revenue (Frey et al. 2018; Rejesus and Goodwin 2019).[8]

The second is a cost share program for site preparation and planting of trees. There are numerous federal and state programs that can be used to offset a portion of these costs. For simplicity, we assumed that a cost share program would cover 50% of the costs of site preparation, planting, and competition control. 50% cost-share payments are typical in federally-administered programs such as the Conservation Reserve Enhancement Program (CREP) (FSA 2018), and similar to the 40% paid by North Carolina's state Forest Development Program (NCFS 2018).

Carbon payments

We modeled the impact of a policy that is not common in the U.S., but has been the subject of economic debate and research, a payment for carbon sequestered from the atmosphere by trees. Payment schemes and mechanisms are likely to vary, so we modeled a simple hypothetical scheme under which a manager would be paid per ton of carbon dioxide (tCO_2) sequestered each year as trees grow. However, if timber is harvested, or carbon lost from other tree mortality, the manager must repay the amount of carbon lost at the same price. Although this hypothetical scheme does not exactly mirror any specific forest carbon offset protocol on the voluntary or compliance market, protocols for calculating carbon offsets are highly variable (Parajuli et al. 2019; Yankel 2018), and this approach does provide a straightforward way to link the carbon value to the timber growth variable already included in the model without necessitating a separate variable in the model. We assumed a price of \$10/m^3 merchantable timber, which translated to roughly \$7.25/tCO_2 sequestered,[9] which is intermediate between current voluntary and compliance market credits (Parajuli et al. 2019) (code modifications described in Appendix 1).

Results

Parameter estimation

Results of the parameter estimation are given in supplemental Tables S1-S3. Of the three commodity crops, soybeans were found to be the most profitable on average in real 2013 dollars from 1979 to 2015, and corn the least profitable, based on historic yields from Halifax County, prices from North Carolina, and costs from the Southeast. Soybeans also had the lowest standard deviation, so was the least risky.

Monte-Carlo simulation and scenarios

The Monte-Carlo simulation in ALLEY 2.0.1 generated n = 25,000 replications of the m = 40 years of financial returns elements. Figure 1 displays crop financial returns for the three crops using historical data for 1977–2015 and a single replicate of the

[8] The benchmark revenue for individual coverage is the average of the three middle annual revenues per unit land area from the past 5 years. Revenue is calculated by multiplying the average annual yield for that producer and crop times the national average market price.

[9] 1.38 tCO_2e/m^3 merchantable pine timber. Conversion based on the equation: $CO_2 = mt \cdot d \cdot BEF_2 \cdot (1 + R) \cdot CF \cdot C$

CO_2 is t of carbon dioxide; m is m^3 merchantable timber; d is the bone-dry density of pine timber = 0.47 t/m^3; BEF_2 is the biomass expansion factor = 1.3 t aboveground biomass/t merchantable timber; $1 + R$ is the conversion from aboveground to total biomass (R is based on root-shoot ratio) = 1.23 t total biomass/t aboveground biomass; CF is the carbon fraction = 0.5 t C/t total biomass; C is the C to CO_2 conversion = 3.67 t CO_2/t C.

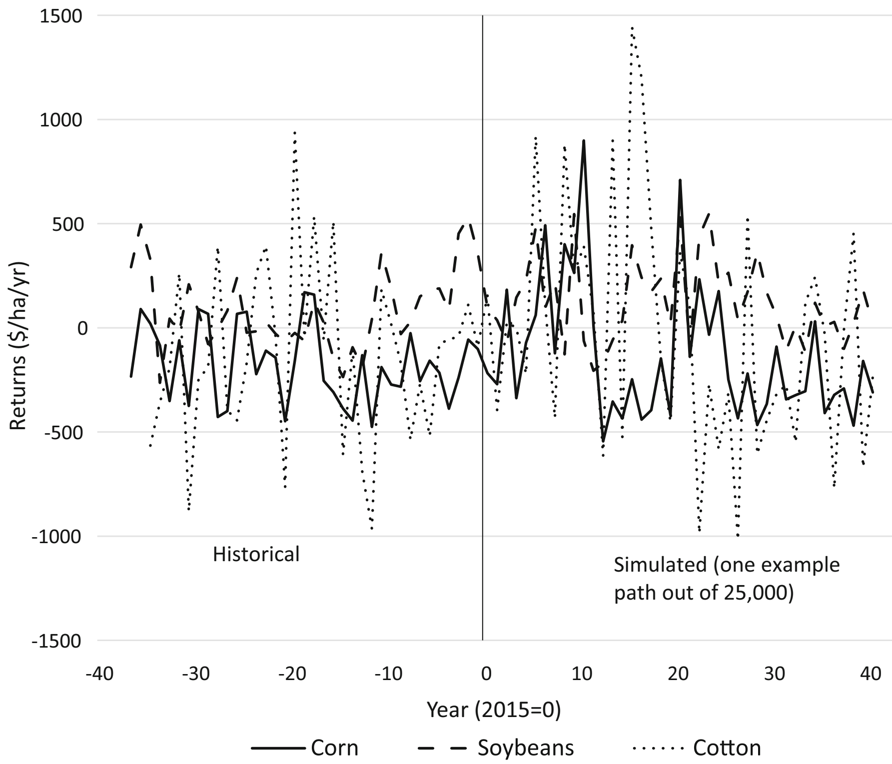

Fig. 1 Historical (1977-2015) (ERS 2016) and one example simulated path of monocropping financial returns (revenues minus costs, in real 2013 dollars), for three crops, using Halifax County average yields, North Carolina output prices, and Southeast average input costs. In the ALLEY 2.0.1 model, future paths were simulated 25,000 times to find the distribution of financial returns

40 year time horizon, as an example. Results for AEI, SEV, government payments, and timber rotation for the scenarios are reported in Table 4, and crop selection in Table 5. Cumulative distributions of the SEVs (Figs. 2, 3, 4, 5, 6) for monocropping, alley cropping, and loblolly pine plantation are based on ordering results from 25,000 realizations of the Monte Carlo model.

In our simulation, using our assumptions and across various scenarios, monocropping (single species row crop) tended to have higher overall profits (as measured by AEI or SEV) than alley cropping when using a fixed, 40-year rotation, which was higher than a loblolly pine plantation. In the base case, monocrop had a mean AEI of $275/ha/year versus $37 for loblolly pine plantation (40-year rotation) and $24 for loblolly pine alley crop (12.2 m alley and 40-year rotation). The pine plantation had the lowest risk (as measured by standard deviation) in all scenarios. In the base case, pine plantation had a standard deviation of AEI of $40/ha/year compared to $104 for alley cropping and $248 for monocropping. It is also of interest that while alley cropping did have lower risk than monocropping in the base case, in some cases alley cropping had higher returns and higher risk than monocropping, particularly the cases including a 24.4 m alley and optimal rotation.

Base case

In the base case (Tables 4 and 5, Fig. 2 with the alley and pine systems labeled as "40-year rotation"), monocropping and loblolly pine plantation both have higher mean AEI than alley cropping with 12.2 m alleys. Monocropping first-order dominates alley cropping, and pine plantation second-order dominates alley cropping. That is, all managers would prefer monocropping to alley cropping, and all risk-averse managers would prefer pine plantation to alley cropping.

Soybeans and cotton were about equally selected in monocropping with about 40% each, but soybean was more commonly selected in alley cropping with 52% selection. This is because the competition between trees and crops affected soybean financial returns to a lesser extent than cotton. While all yields were affected by the same proportional amount, soybeans

Table 4 Annual equivalent income (AEI), soil expextation value (SEV), mean government payment, and mean timber rotation for each system and scenario (25,000 simulations of up to 40 years each)

	Mean AEI[a] ($/ha/year) 5% discount rate	SD of AEI	Mean SEV[a] ($/ha)	SD of SEV	Mean gov. payment ($/ha/year)	Mean timber rotation (year)
1. Base case						
Monocrop	275	248	5500	4950	–	–
Pine—40-year rotation	37	40	740	800	–	40
Alley—12.2 m–40-year rotation	24	104	480	2070	–	40
2. Optimal rotation						
Pine—optimal rotation	134	57	2690	1150	–	25.6
Alley—12.2 m—optimal rotation	146	158	2920	3160	–	22.1
3. Increase alley width						
Alley—24.4 m –40-year rotation	163	181	3260	3630	–	40
Alley—24.4 m—optimal rotation	365	291	7310	5830	–	20.4
4. Include specialty crops						
Monocrop	340	226	6800	4510	–	–
Alley—24.4 m—optimal rotation	426	262	8530	5230	–	21.7
5. Commodity and cost share payments						
Monocrop	458	267	9150	5340	208	–
Pine—optimal rotation	164	56	3280	1120	18	24.9
Alley—24.4 m—optimal rotation	512	300	10,230	6000	165	20.2
6. Carbon payments						
Pine—optimal rotation	177	60	3550	1210	61	28.7
Alley—24.4 m—optimal rotation	384	276	7690	5520	52	23.1

[a]Includes value of government payments

is lower-cost and lower-revenue, so the reduction in yield affects total financial returns to a lesser extent.

Optimal rotation

The optimal rotation scenario (Tables 4, 5 and Fig. 2, with the alley and pine systems labeled as "optimal rotation") unambiguously improves AEI by $97/ha/year in the case of loblolly pine plantation and $122 for alley cropping, and indicated by a rightward shift in the CDFs, compared to the base case fixed "40-year rotation." This was pair with an increase in risk as the standard deviation of AEI increased by $17/ha/year and $54, respectively. Alley cropping systems had shorter "optimal" timber rotations than the loblolly pine plantation (22 vs. 26 years). This may be due to two differences. First, the trees spaced further apart grow more quickly as individuals, and are at optimal harvest age sooner. Second, as trees get older, financial returns from crops are reduced so it becomes optimal to harvest trees sooner to return to better productivity of agricultural crops.

When considering optimal rotations for loblolly pine and alley cropping systems, neither system dominates or is dominated by the other, or by monocropping. This means managers of different

Table 5 Percent of total years that each crop is selected. Numbers may not sum to 100% due to rounding

	Corn (%)	Soybeans (%)	Cotton (%)	Specialty 1 (%)	Specialty 2 (%)
1. Base case					
Monocrop	21	39	40	–	–
Alley—12.2 m –40-year rotation	22	49	29	–	–
2. Optimal rotation					
Alley—12.2 m—optimal rotation	24	52	23	–	–
3. Increase alley width					
Alley—24.4 m –40-year rotation	21	44	35	–	–
Alley—24.4 m—optimal rotation	24	46	30	–	–
4. Include specialty crops					
Monocrop	18	25	28	11	18
Alley—24.4 m	18	28	16	24	14
5. Commodity and cost share payments					
Monocrop	24	37	39		
Alley—24.4 m—optimal rotation	27	43	30		
6. Carbon payments					
Alley—24.4 m—optimal rotation	24	45	31		

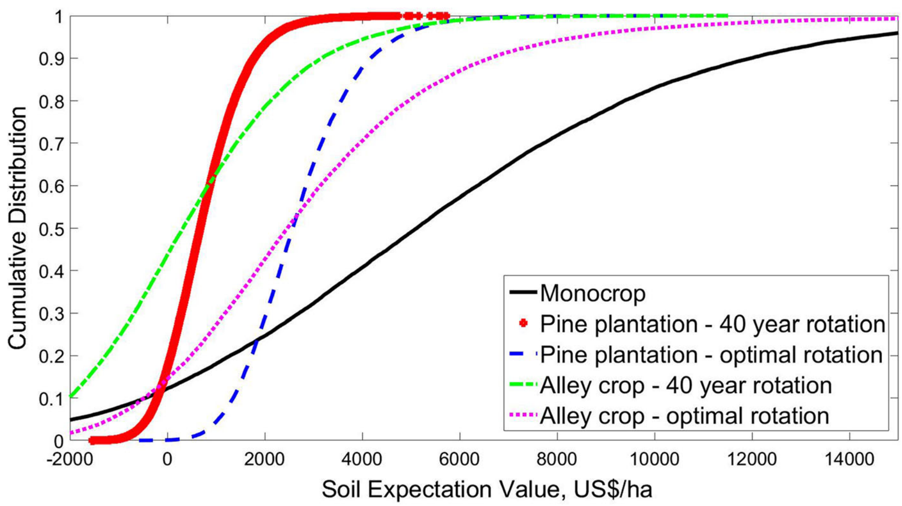

Fig. 2 Scenarios 1 and 2: Base case and optimal rotation. Cumulative distribution functions of monocropping, pine plantation, and 12.2 m alley cropping

levels of risk aversion might choose any of the three systems. However, given the higher monocropping average AEI ($275 vs. $146/ha/year) and moderately higher risk (standard deviation of AEI $248 vs. $158/ha/year) compared to alley cropping (with 12.2 m alley and optimal rotation), it seems likely that most managers would prefer monocropping to alley cropping.

However, the overall financial profile alley cropping with the widest alleys described below (24.4 m) did outperform monocropping when the assumption of optimal rotation was included (mean AEI $365 vs. $275/ha/year). A realistic distribution for alley cropping is likely to be intermediate between the fixed rotation and the optimal rotation, as most managers

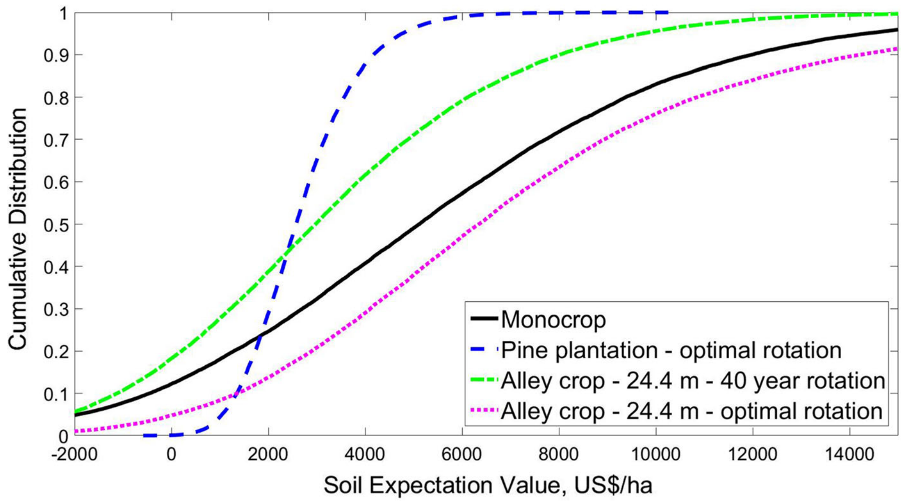

Fig. 3 Scenario 3: Increase alley width. Cumulative distribution functions of monocropping, pine plantation, and 24.4 m alley cropping (twice the width of the base case assumptions). Monocropping and pine plantation assumptions are identical to the base case and optimal rotation case, respectively

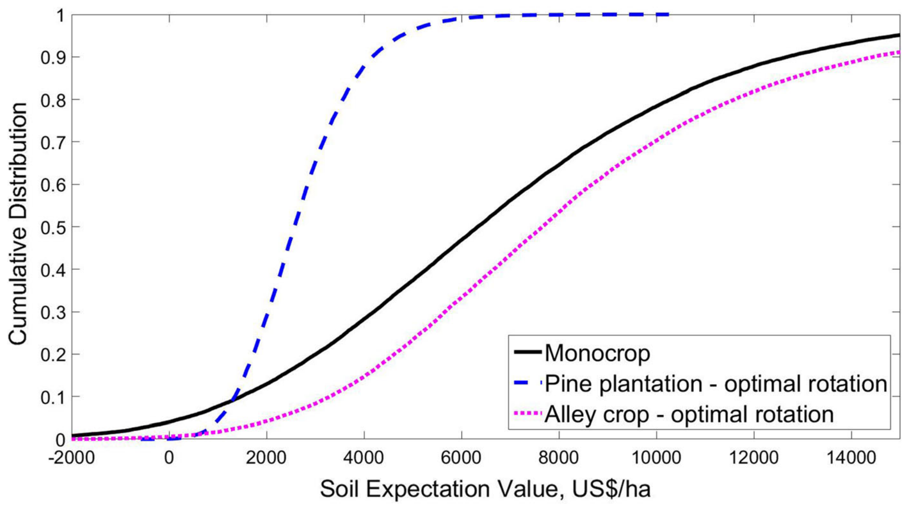

Fig. 4 Scenario 4: Specialty crops. Comparison of cumulative distribution functions of monocropping, pine plantation, and 24.4 m alley cropping, optimal rotation for the pine and alley cropping, including the option of using two specialty crops in the monocropping and alley cropping systems

will allow some flexibility in rotation lengths, but will not have perfect knowledge of the future.

Alley width

The increase in mean AEI from the 12.2 m alley to 24.4 m alley is meaningful and relatively large, equaling about $139/ha/year under the fixed rotation and $219 under the optimal rotation (Table 4). However, at the same time risk, as measured by standard deviation of financial returns more than doubles, putting alley cropping on par with monocropping. The wider alleys also change the proportion selected crops in the alley, shifting them slightly closer to the monocropping selection (Table 5).

Assuming an optimal rotation, alley cropping with wide alleys (24.4 m) does first-order stochastically dominate monocropping; that is, the CDF is to the

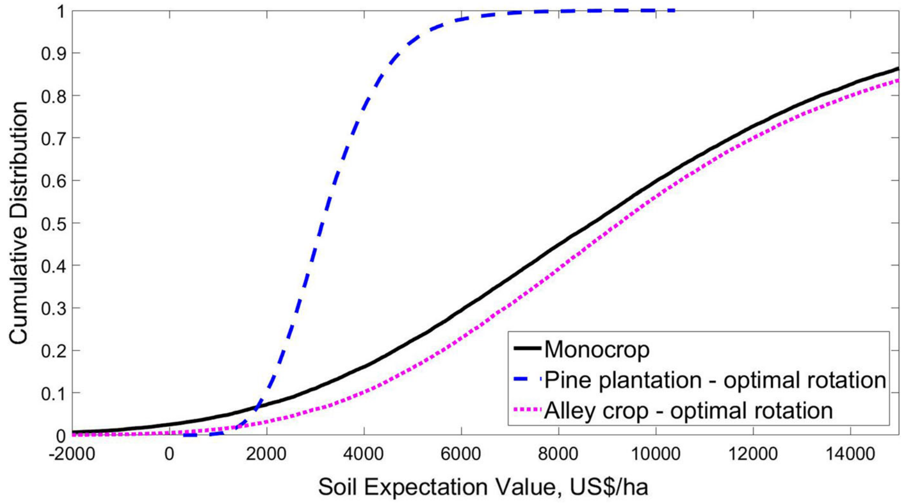

Fig. 5 Scenario 5: Commodity and cost share payments. Comparison of cumulative distribution functions of monocropping, pine plantation, and 24.4 m alley cropping

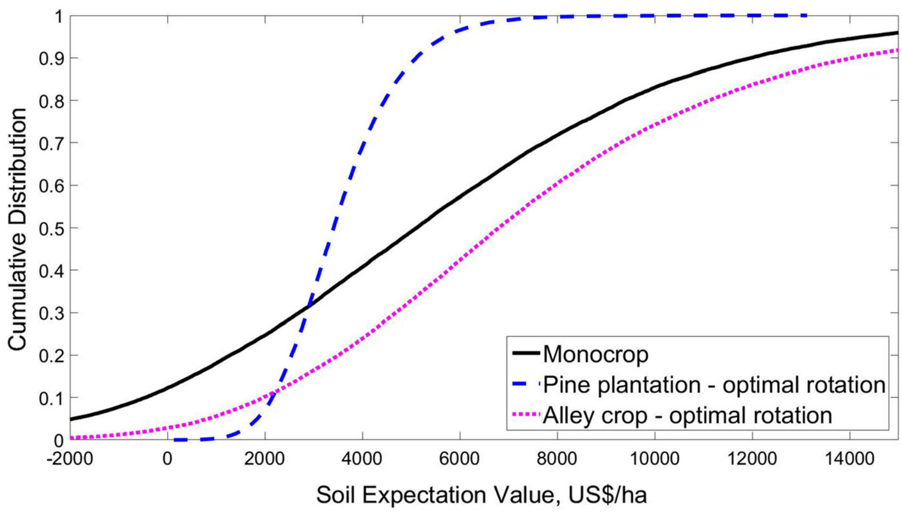

Fig. 6 Scenario 6: Carbon payments. Comparison of cumulative distribution functions of monocropping, pine plantation, and 24.4 m alley cropping

right, and any manager who prefers higher financial returns would prefer it (Fig. 3). However, under a fixed, 40-year rotation, monocropping nearly first-order dominates alley cropping.[10] This shows that management, flexibility, and knowledge of the markets are extremely important. Although the optimal rotation assumptions are unrealistic, this demonstrates that alley cropping could be potentially competitive with monocropping, if done with skill and information.

Specialty crops

We expected that specialty crops should unambiguously improve the profits of both monocropping and alley cropping because they provide an extra alternative that can be utilized if performing well, but producers are never obliged to use, and this appears to be the case (Table 4). Compared to Fig. 2, the

[10] The CDFs do cross in the extreme lower tail, not shown in Fig. 3.

distributions for monocropping and alley cropping in Fig. 4 are shifted to the right, increasing mean AEI by $65/ha/year for monocropping and $61 for alley cropping. Still, they do not stochastically dominate the loblolly pine plantation distribution because the left-most tails of both monocropping and alley cropping are to the left of pine plantation, so there still could be some risk averse individuals who would prefer pine planation (since pine plantation does not change because of specialty crops, in Table 4 refer to the pine plantation results from Scenario 1). However, this would be a smaller group of (highly risk-averse) individuals.

The addition of specialty crops did alter the crops most often utilized in the systems (Table 5). Most notably, Specialty crop 2 was used approximately 18% of the time in the monocropping and 14% in alley cropping, and as a result decreased the percentage of the three commodity crops. Specialty crop 2 has a profile of a crop that is "countercyclical"—it tends to perform well in years when other crops do not, even though its average financial returns are lower. Specialty crop 1, which performs best in the microclimate of an alley with moderate-size trees, was used 24% of the time in alley cropping, but only 11% of the time in monocropping.

Commodity and cost share payments

Adding government payments from the ARC-IC and reforestation cost-share programs increased the mean financial returns of all three systems (Table 4). AEI of monocropping increased $183/ha/year, loblolly pine plantation $30, and alley cropping $147, relative to the closest comparison case (without specialty crops). Interestingly, however, standard deviation did not decrease significantly, which we might expect from a program such as ARC, which is designed to limit down-side risk. Government payments had the largest positive effect on monocropping financial returns, pushing the CDF very close to the alley cropping "optimal rotation" (Fig. 5). Since the "optimal rotation" is based on unrealistic assumptions, a more realistic CDF of alley cropping would likely be below that of monocropping when government payments are included. This suggests government payment programs inhibit alley cropping adoption. Under the modeled policies, payments from government averaged about $208/ha/year for monocropping, $18/ha/year for loblolly pine plantation, and $165/ha/year for alley cropping.

Carbon payments

Carbon payments were assumed to benefit alley cropping and loblolly pine plantation, but not monocropping (Fig. 6). Compared to the optimal rotation pine and alley cropping (24.4 m alley) scenario, inclusion of carbon payments under our assumptions increases AEI by about $43/ha/year for loblolly pine plantation and $19 for alley cropping, without meaningfully changing the risk as measured by standard deviation (Table 4). Government payments averaged $61/ha/year for pine plantation and $52 for alley cropping. Thus, carbon payments as modeled with our assumptions, are smaller than the modeled Farm Bill commodity payments for monocropping or alley cropping, but larger than the cost-sharing for loblolly pine plantations. The carbon payments had the effect of extending the average optimal rotation by about 3.1 years for pine and 2.7 years for alley cropping (Table 4).

Discussion

In terms of management choices, alley cropping was most competitive with monocropping when a wider, 24.4 m alley and optimal rotation were considered. Narrow alleys and fixed timber rotations make alley cropping economically infeasible for managers, compared to the alternatives considered here. The wider alley is a management choice that makes a large difference in outcomes, increasing AEI by up to $210/ha/year in the assumed region, market, and site conditions. Adding flexibility in determining the year of timber harvest also increases AEI significantly, by up to $200/ha/year, which represents the best case. The reader should exercise some caution when interpreting the "optimal rotation" scenarios, since they are not directly comparable with the monocropping scenarios because the alley cropping "optimal rotation" assumes perfect knowledge of the future by the manager, whereas the monocropping does not.

Inclusion of potential specialty crops improved financial returns for both alley cropping and monocropping relative to loblolly pine plantation and relative to scenarios without inclusion of specialty crops, but did not seem to make much difference in the comparison between alley cropping and monocropping. Specialty crop 1, which performs better under microclimate conditions in a more mature alley cropping system could be utilized to increase profits in an alley cropping system. In this case, it is incumbent upon researchers, extension educators, technical service providers, and producers to do market and other background research in their regions to test interactions and find potential crops that might perform relatively well in an alley cropping microclimate, and have some markets for sale. Options might include certain vegetables, fruits, botanicals, cut flowers, mushrooms, annual hay crops, or annual biomass crops (Workman et al. 2003; Blazier et al. 2012; Haile et al. 2016).

A management choice that is implicit in all our scenarios, through the assumption of competition profile 1, is that the producer would not undertake additional management to limit the competition between trees and alley crops. Installing an underground root barrier, deep disking to train tree roots, pruning roots or branches, or other activities have been shown limit this competition, thereby increasing the crop yields (Zamora et al. 2008). However, potential negative impacts on tree yields or costs of these management approaches were unknown, so we chose to ignore these potential management activities for the current study. As such science and cost information becomes clearer, it could be incorporated into a future version of the ALLEY model.

Government policy can affect financial returns to management of forest and agricultural lands. The current typical policy regime, which includes ARC payments to monocropping producers and cost-share payments for loblolly pine plantations (Rejesus and Goodwin 2019; Jacobson et al. 2009), tends to favor monocropping. We assumed that alley cropping would be deemed eligible for both types of payments, an assertion that may not hold true in all circumstances. Even so, the average payments to alley cropping would not be as high as for monocropping.

Interestingly, in many of the scenarios alley cropping had a larger standard deviation of potential financial returns than monocropping. This suggests that risk mitigation, which has been hypothesized and promoted as a major potential benefit of alley cropping (MacFarland 2017; Workman et al. 2003), may not actually play out that way. A farm that diversifies by having several different monocropping parcels, with various different products at any given time, would also have lower risk than this model, which is based on choosing only one crop per year. Loblolly pine plantation, while generally having lower average yield, had lower risk than both monocropping and alley cropping in all the scenarios (Table 4). It was not second-order dominated because alley cropping and monocropping had larger low-end tails in the CDF, so extremely risk-averse managers in this area of North Carolina would potentially prefer loblolly pine plantations over the other two options. The same may be true for other areas across the South depending on specific situations related to the site quality, tree species, crops, policy, and climate/environmental variables.

Economic feasibility of alley cropping will depend greatly on a manager's knowledge and skill. Monocropping stochastically dominates fixed-rotation alley cropping. Therefore, all producers would prefer monocropping over fixed-rotation alley cropping. To get closer to the "optimal rotation" scenario implies having a strong sense of future market conditions.

While alley cropping may have higher mean profits than loblolly pine plantations in our study, replacement of loblolly pine plantations with alley cropping is also not likely. Partially this is because alley cropping does not second-order dominate pine plantation, so some risk averse producers are likely to prefer pine plantation. In addition, (1) many pine plantations are on agriculturally marginal land (Li and Zhang 2007), and (2) many family forest owners with pine plantations are either absentee or work somewhere away from their land and are not interested or available to manage annual crops on a frequent basis (Butler et al. 2016; Snyder et al. 2020).

Although this research approach allows for modeling many permutations of systems, management regimes, and policies, it has limitations. The Monte Carlo model is only as good as the underlying data and assumptions. The historical data used were the best available, but all sources used geographic averaging of yields and prices. This can lead to underestimates of single-farm yield variability (Just 2003), so actual risk may be higher than our estimates. There are numerous simplifying assumptions made, which allow computational tractability, but lose some nuance. The equations modeling autoregression and trends of prices and yields may be imperfect models of the factors that influence how price and yield change from year to year. Some of the assumptions are based on relatively limited research and the authors' best estimates, including the quantification of interspecific competition. Finally, some aspects of alley cropping lacked research to be able to include in the model, so they had to be excluded from consideration, such as the potential impact of cultivation of understory crops on the growth of trees, or the impact of fertilization of crops on trees.

Conclusions

We constructed a mathematical model to simulate financial returns and risk for a hypothetical versatile loblolly pine alley cropping system, using real-world data from Halifax County, North Carolina for three commodities and pine timber, and compared those results to conventional loblolly pine plantations and monocropping systems. Our model allowed producers to shift annual crops to obtain better profits under stochastic, changing market conditions.

On average agricultural land in North Carolina, alley cropping may be of value to certain producers, but we find those possibilities to be somewhat limited. Alley cropping performed the best financially—with higher mean financial returns than monocropping and roughly similar standard deviation—with larger alleys and when we made unrealistic assumptions about perfect knowledge for finding the optimal timber rotation. This indicates alley cropping may have the most potential for highly skilled and knowledgeable producers. However, in our study, alley cropping with loblolly pine does not meaningfully reduce financial risk relative to monocropping. Furthermore, current government policies and potential future carbon payments did not substantially tip the balance towards alley cropping. In the absence of policies specifically encouraging alley cropping as an alternative, individual producers must decide for themselves if their individual stewardship ethic places that much value on a potentially more environmentally-friendly system.

Alley cropping does present numerous management options, of which we have tested only a few here. To be sure, other tree species such as black walnut in the U.S. Midwest, and alley crops such as berries or biomass crops may present new opportunities from a financial perspective, and could be tested in the future. Different spatial and temporal designs, management strategies to limit inter-specific competition offer other potential opportunities that could be tested experimentally and modeled in future simulations.

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