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Alley cropping as an alternative under changing climate and risk scenarios: A Monte-Carlo simulation approach

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ABSTRACT

Alley cropping is an agroforestry system in which annual crops are grown in alleys between rows of woody perennials for timber or other products, which can provide ecosystem services and help farmers diversify outputs. But is alley cropping a financially viable alternative to monocropping? To answer this question, a Monte Carlo model of financial risk and returns was used to understand how this diversification of outputs might help farmers in the southeast United States adapt to future scenarios in which agriculture or forestry may become more risky due to a changing climate or other factors. Traditional monocropping had the highest mean returns in the base scenario (based on current risk conditions), but the highest risk. Pine plantations had the lowest returns and lowest risk, and alley cropping was intermediate (mean soil expectation values of $5513 for monocropping, $3955 for alley cropping, and $2693 for pine plantations). The model results showed that traditional monocropping does not stochastically dominate alley cropping in any of the risk scenarios, meaning that alley cropping may have a place for risk-averse farmers. Furthermore, in the scenario in which the downside risk of annual crop production is increased – perhaps due to increased frequency of floods, droughts, etc. – alley cropping mean returns are higher and risk lower than traditional monocropping (mean soil expectation values of $2951 and $2911, respectively, and pine plantations at $2688), meaning any risk averse farmer might prefer alley cropping to monocropping.

1. Introduction

Alley cropping is an agroforestry system in which annual crops are grown in alleys between rows of woody perennials for timber or other products. This diversification leads to potential ecosystem benefits including soil and water conservation (Malézieux et al., 2009). For instance, by planting trees on soils subject to erosion, alley cropping allows for the conversion of marginal agricultural lands into high value timber stands over time (Wei et al., 2007). Alley cropping systems including trees also allow for greater Carbon (C) sequestration (Oelbermann et al., 2006) and improved nutrient recycling, reductions in nutrient leaching in soils, improved soil fertility, and sustained levels of crop production (Kang, 1997). In tropical areas where nutrients cycle through the soil more quickly, trees as hedgerow products help to retain nutrients in the soil for longer periods of time (Ospina, 2017). Furthermore, in addition to timber, trees can produce biofuels, fruits and nuts, or other specialty crops (Zinkhan and Mercer, 1996).

While alley cropping has been known for the ecosystem services it offers, it has also been shown that this diversification of land use permits for long term investment in timber products which allows for alley cropping to compete financially with monocropping on certain lands (Phimmavong et al., 2019). However, few studies exist which explore possible impacts on the viability of alley cropping, particularly from a financial perspective (see, e.g., Cary et al., 2014). This deficiency in the literature is a particularly important barrier to overcome if alley cropping, and the ecosystem benefits which it offers, are to be implemented by land owners, as agriculture in general is an inherently risky endeavor.

Of all the potential risks faced by agriculture, climate change poses perhaps the most persistent and severe threat. While these impacts have been studied in the context of monocropping (Adams et al., 1998; Asseng et al., 2019) and timber production (Kirilenko and Sedjo, 2007; Venäläinen et al., 2020), the impact of climate change on alley cropping has yet to receive much attention. In monocropping regimes, climate change has been shown to have numerous impacts on agricultural production, including increased photosynthesis and evapotranspiration due to elevated carbon dioxide (CO2) levels and increases in damaged crops due to heat, drought, rain and hail storms, and other catastrophic

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events (Adams et al., 1990). Previous works have modeled the impacts of climate change on agricultural yields and returns through two primary means: broader risk distributions (White et al., 2011) and higher probabilities of catastrophic events (Xu et al., 2011).

The goal of this paper is to understand how alley cropping may mitigate the inherent risks faced by agriculture under future climate scenarios. This will be done by forecasting returns from alley cropping, monocropping, and pine plantations under possible future climate scenarios. Possible future scenarios due to climate change include an increased risk of catastrophe such as hurricanes, fires, and droughts, and worsened conditions for agriculture generally. The ALLEY 2.0 Model from Frey et al. (2018) was used to simulate returns under these conditions, generating data to use to study how alley cropping may mitigate the inherent risks faced by agriculture under future climate change scenarios.

2. Background

2.1. Alley cropping

Alley cropping, in certain circumstances, can be a financially competitive land use methodology that offers greater ecological benefits than traditional monocropping. Financial advantages of alley cropping are numerous and differ across the globe. For instance, in developing nations where wood burning is commonly used for cooking, the adoption of alley cropping has led to reduced fuel wood purchases (Ospina, 2017). This is particularly significant as Thorlakson and Neufeldt (2012) noted that women in Kenya often walked in excess of 20 km just to buy fuel wood. This is a global phenomenon; Dhakal et al. (2012) found that alley cropping systems are often used to provide fuel wood in Nepal.

Despite the many ecological and financial benefits of alley cropping, the adoption of alley cropping varies drastically across the world. Even though several studies have assessed the determining factors of alley cropping adoption (e.g., Dhakal et al., 2015), adoption remains slow in many parts of the world. The additional uncertainty of the impact of climate change on agroforestry practices further complicates the decision to adopt alley cropping. While in some cases alley cropping provides clear benefits in confronting climate change, especially in developing nations such as much of sub-Saharan Africa (Mbow et al., 2014), the benefits are less clear in places such as the United States where government subsidies can disincentivize transition from monocropping to alley cropping since individual farmers will value crop productions differently than market prices (Mercer et al., 2014).

The primary measures of the financial viability of an agroforestry system are the net present value (NPV) and the soil expectation value (SEV). These financial measures can be formalized by the equations below (Cubbage et al., 2014; Frey et al., 2018) in which the parameter r represents the discount rate, the parameter m represents the maximum time horizon for a pine plantation, and the parameters $ret_{(crop,t)}$ and $ret_{(tree,t)}$ represent the returns in year t from the alley crop and tree components, respectively.

$$NPV = \sum_{t=0}^{m} ((ret_{(crop,t)} + ret_{(tree,t)}))/(1 + r)^t \tag{1}$$

$$SEV = NPV + NPV/((1 + r)^m - 1) \tag{2}$$

Clearly annual alley crop returns and the tree survival rate are crucial to the financial success of alley cropping. However, each of these components face unique risks under future climate models that will impact the financial viability of all agroforestry models, including alley cropping. These risks include shifts in climate, including temperature and precipitation changes, as well as an increased probability of catastrophic events, such as hurricanes and major droughts, all of which can have a significant impact on the financial viability of alley cropping particularly, and agroforestry in general.

2.2. Risk and catastrophic events

Agricultural prices are known to be inversely correlated with yield, as yield is spatially correlated and reduced supply will drive prices up (Goodwin and Ker, 2002). Crop yield data tend to show negative skewness (Goodwin and Ker, 2002; Goodwin, 2009), which may be because of biological limits on production that blunt the positive tail and catastrophic risks that stretch the lower tail. An alternative, is to model normal-year and catastrophic-year yields as separate sub-distributions within the broader yield distribution.

Timber yield risk, other than catastrophic events, has received less direct attention in the literature. However, typical growth and yield models, based on regression models of timber yield as a function of tree age, stand density, measures of soil productivity, and other variables, do report standard errors, that is, variability or risk in growth and yield. In the forestry risk literature, therefore, yield risk is often described as "growth prediction error" (Pasalodos-Tato et al., 2013).

Catastrophes due to natural hazards can be considered a subset of yield risks. Catastrophic risks are considered to be those which are discrete-time events that have potential to destroy much or all of an agricultural or tree crop. These might include droughts, floods, ice or hail storms, wind storms, and fires. One could model catastrophic risks as simply the tail of yield risks in a single distribution; however, Ker and Goodwin (2000) suggest that catastrophic years may be better represented as separate sub-populations from yields in non-catastrophic years.

In forestry, Chen et al. (2014) model the expected loss from a catastrophic hazard in a given time period as $E(Loss) = P(z = 1)E(loss|z = 1)$, where $P(z = 1)$ is the probability of an event occurring, and $E(loss|z = 1)$ is the expected loss from an event conditional on it occurring. Chen et al. (2014) found the average forest area burnt by fires in Florida to be about 1% per year.

While costs of inputs implementing agriculture or forestry practices can vary from year to year, little literature considers cost risk independently from revenue risk. Farmers generally consider input costs to be a less important source of risk than yield and price risks as a land manager has relatively greater information about the costs before he implements a system (Goodwin and Ker, 2002).

3. Data

In order to create the most realistic models possible, they were based on historical data from various sources. The historical data used provided yields and prices for all crops included in the model. However, the data set provided yields and prices for both cotton lint and cottonseed. To address this, historical annual cotton revenue was calculated by taking the sum of revenues for both cotton products. An imputed price of cotton lint was then found by dividing total cotton revenues by the yield of cotton lint. The ALLEY 2.0 Model can then model cotton lint yield as the agricultural product and the imputed price as the price, a price inclusive of the value of cottonseed. This paper focuses on the coastal plain region of the US Southeastern states of North Carolina and Virginia. Agroforestry in general is seeing new interest in these states. Most research and extension attention has focused on silvopasture and forest farming, yet alley cropping may have some similar benefits to both. Also, a pair of new alley cropping demonstration sites have been established in North Carolina (Cubbage et al., 2012; Pollock, 2012), generating some interest among researchers, producers, and technical service providers. Halifax County, NC was selected as the test county for the simulations because it is a relatively typical agricultural county in the upper coastal plain, near the border of the two states, and historically has been among the top-producing counties of numerous crops in North Carolina. The data obtained is as specific to Halifax County as possible.

3.1. Crop component

Literature on alley cropping was reviewed and a few key informants in North Carolina and Virginia were interviewed to determine which crops might be used in alley cropping systems (Cubbage et al., 2012). The most well-known potential alley crops, with the most data and past research available are commodity row crops traditionally grown in this region (NASS, 2020). Three crops that are commonly planted in this region were selected: corn, soybeans, and cotton. These crops have been studied in alley cropping systems in the United States to varying extents. Additionally, hypothetical "specialty" crops were constructed for the model. These represent products that have markets limited geographically or in scale, and might include fruits and vegetables, cut flowers, hay, or something else. The addition of specialty crops permits us to determine the properties of a potentially successful alternative to the selected row/cereal crops. The specialty crop returns element distributions were completely hypothetical and not based on real data.

For the three row crops, historical agricultural data for each returns element (input cost, output price, and yield) was obtained at the smallest geographic level for which it was possible to obtain quality data. This resulted in input costs at the regional level, output prices at the state level, and yield at the county level. Input cost data for the Southeast/Southern Seaboard region was from ERS (2016). These data have the benefit of being based on real costs and revenues rather than forecasts and comprise a relatively consistent database in the region of interest, going back 35 years or more.

Per the instructions of Frey et al. (2018), all production costs except the opportunity costs of unpaid labor and land are included. Output price data for North Carolina and yield data per area planted for Halifax County were obtained from NASS (2016). Input costs and output prices were adjusted to real 2013 dollars using the Consumer Price Index (CPI) (US BLS, 2014). The mean and standard deviation of crop output prices, yields, and input costs for 1976–2015 are given in Table 1. (See Figs. 1 and 2.)

3.2. Tree component

Since this paper focuses on commercial timber species, and the majority of commercial timber production in the US Southeast is focused on southern pines, loblolly pine (*Pinus taeda* L.) was selected for the tree component. Loblolly has been used in experimental alley cropping systems in the southeastern US (Blazier et al., 2012; Cubbage et al., 2012; Zamora et al., 2009), and the timber is easily marketable. Furthermore, loblolly has the most data available regarding growth and yield models and historic timber prices.

Southern pine pulpwood and sawtimber stumpage prices for 1976–2015 were obtained from NCCE (2014). Forest plantation establishment and management costs were based on NC Forest Service's (2014) "Prevailing rates for sub-practices" list for the Rocky Mount, NC district. These costs were somewhat higher than those in Dooley and Barlow (2013), but thought to be more representative of costs for smaller-scale, family-owned forests in North Carolina. Input costs and output prices were converted to real prices using the Consumer Price Index (CPI) (US BLS, 2014).

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

	Corn	Soybeans	Cotton	Sawtimber	Pulpwood
Mean output price ($/metric ton for crops, $/m^3 for timber)	211	448	2464	57.3	11.1
Standard deviation	*86*	*194*	*1021*	*14.3*	*1.4*
Mean yield (metric tons/ha)	4.46	1.77	0.72		
Standard deviation	*1.07*	*0.37*	*0.22*		
Mean input costs ($/hectare)	1085	673	1956		
Standard deviation	*238*	*157*	*459*		

4. Methods

4.1. Monte-Carlo model

The simulations were performed using the ALLEY 2.0 software suite for MATLAB outlined in Frey et al. (2018). The ALLEY 2.0 software suite uses a Monte Carlo approach to estimate and compare expected values and distributions of returns for monocropping, alley cropping, and pine plantations under various land management regimes. Using historical data from Halifax County, North Carolina, possible future climate scenarios under climate change are simulated by addressing the potential for increased rates of catastrophe (forest fires, droughts, etc.), and then estimate expected returns from monocropping, alley cropping, and pine plantations in these simulations. Alley crop systems are simulated with alley widths of 24.4 m. Each of these three land use models is simulated independently under a total of 6 different possible future climate scenarios. These six scenarios can be divided into two groups: one group which includes an increased catastrophe probability, and one which does not. Within each group there is a base case scenario which uses model default parameters, a scenario which fattens both tails of the risk distribution, and a scenario which fattens only the lower tail of the risk distribution. It is from this risk distribution that shocks on the yield and price of crops are generated. The results from these Monte Carlo simulations are used to generate distributions which are then used to help us determine how alley cropping can mitigate some of the risks faced by agriculture due to climate change.

Detailed methods on the computer model ALLEY 2.0 in MATLAB are described in Frey et al. (2018). In summary, for the crop component, a Gaussian copula (Frees and Valdez, 1998) is used to model all returns elements - output prices, yields, catastrophic yields, input prices - for all crops, starting from shocks generated randomly from a single multivariate normal distribution function. The shocks are then converted into values for each returns element using distribution and auto-regression-trend functions estimated with historical data (Frey et al., 2018). This creates a correlated joint distribution of the risk elements. AR1 autoregression was used to derive negative and positive exponential time trends for prices and yields, and AR1 autoregression without time trends was used for costs. For the distributions of shocks, a log-normal distribution was assumed for prices, a beta distribution for yields, and a normal distribution was used for costs.

For the timber component, sawtimber and pulpwood price and timber input costs were modeled as part of this joint distribution. However, timber yield was modeled independently based on a growth and yield model, with corresponding random error terms, found in Westfall et al. (2004) for young pine (before the onset of intraspecific competition), and in Burkhart et al. (2008) for older pine. To those models, possibility of forest catastrophes (fire, pests, etc.) was added. These catastrophic events are assumed to occur with a fixed probability and kill a random proportion of trees from a normal distribution with fixed mean and standard deviation. Forest plantation costs were drawn from a normal distribution with fixed mean and standard deviation.

In the alley crop component, the competition function is employed using the recommended settings for each of corn, soybeans, and cotton given in Frey et al. (2018). Pine prices and harvests and alley crop yields and prices are computed in the same manner as in the timber component and monocrop component, respectively. All parameter changes to monocrop and pine plantation variables made under each scenario are used in each of the alley crop simulation performed under the same scenario.

In order to run the Monte Carlo simulation, parameter estimates from the historical data were first generated. Of the three commodity crops, soybeans were found to be the most profitable on average in real

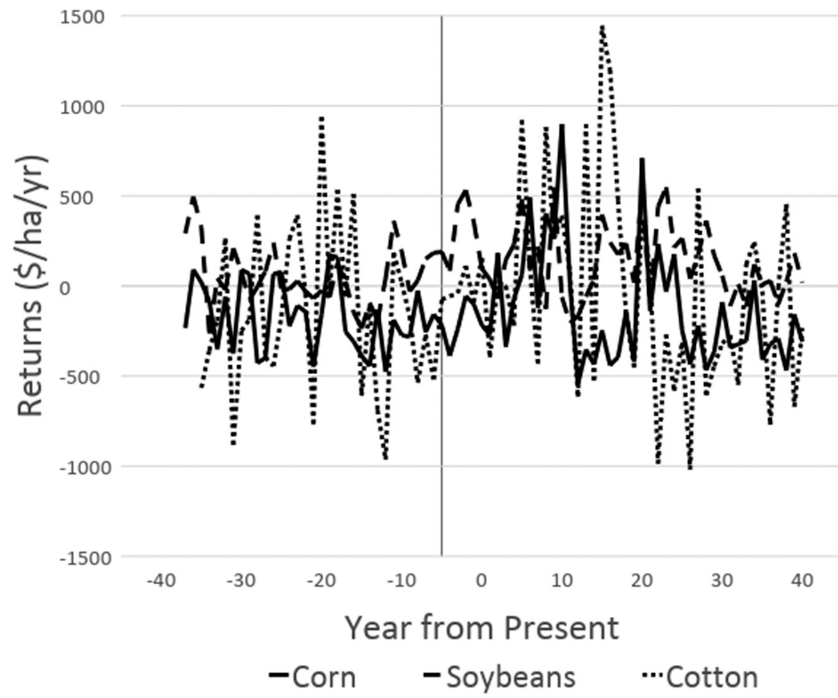

Fig. 1. Historical (1977–2014) (ERS, 2016) and one example simulated path of crop returns (revenues minus costs, in real 2013 dollars), for three crops, using Halifax County average yields, North Carolina output prices, and Southeast average input costs. Future paths were simulated 10,000 times to find the distribution of returns.

2013 dollars from 1979 to 2014, 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 variable or risky.

The output price, yield, and input costs were estimated over a 40-year time horizon run in Monte-Carlo simulation with 10,000 iterations in the ALLEY Model 2.0 (Frey et al., 2018), to determine average and distribution of long-run profits. The primary discounted (5% discount rate) profit indicator calculated was SEV. The average optimal timber rotation and the number of years each crop was selected were also calculated. Three land-use systems were modeled independently (monocrop, alley crop, and pine plantation) under different future climate scenarios. The results of the SEV for all the 10,000 iterations were then ordered by percentile and plotted as a cumulative distribution function (CDF), and the expected value (mean) and standard deviation were calculated. The concepts of first- and second-order stochastic dominance are used to compare the CDFs of different land uses within each scenario, as described below.

Scenarios	Assumptions
Base Case	Current climate conditions hold going forward so that crop yields are unaffected.
Increased Yield Risk: Two-sided	Climate changes including increases in crop yields due to effects such as elevated CO2 levels and decreases in crop yields due to effects such as increased temperatures and altered rainfall patterns.
Increased Yield Risk: Lower tail only	Climate changes include those from the previous scenario with the further assumption that any positive effects on crop yields are negligible; i.e., increased temperatures and altered rainfall patterns fatten the lower tail of the risk distribution.

Fig. 2. A diagram describing the structure of the scenarios and how they interrelate.

Table 2
Results of the model for SEV, 10,000 simulations of up to 40 years each.

	Mean SEV ($/ha)	Stdev SEV	Average timber rotation (years)
Base case			
Monocrop	**5513**	4964	–
Alley crop 24.4 m	3955	3029	20.0
Pine	2693	1158	28.0
Increased yield risk: two-tailed			
Monocrop	**5389**	4928	–
Alley crop 24.4 m	3974	2979	19.9
Pine	2698	1155	28.0
Increased yield risk: lower tail only			
Monocrop	2911	4945	–
Alley crop 24.4 m	**2951**	3140	20.5
Pine	2688	1140	28.0
Base case with increased catastrophe probability			
Monocrop	**5377**	5097	–
Alley crop 24.4 m	3883	3091	20.0
Pine	2683	1170	27.8
Increased yield risk: two-tailed with increased catastrophe probability			
Monocrop	**5505**	4541	–
Alley crop 24.4 m	3920	2745	19.9
Pine	2684	1160	27.9
Increased yield risk: lower tail only with increased catastrophe probability			
Monocrop	**2966**	4465	–
Alley crop 24.4 m	2934	2697	20.4
Pine	2656	1141	27.8

The largest mean SEV is boldened.

4.2. Scenarios

The scenarios simulated in this study can be categorized into two groups of three scenarios each, one group which does not assume an increased tree catastrophe probability, and one which does assume an increased tree catastrophe probability. The scenarios in each group include a base case (default parameterization from the model), an increased crop yield risk with both tails of the risk distribution fattened (this accounts for the possibility of both increased yields due to increased CO2 levels as well as decreased yields due to drought), and an increased crop yield risk with only the lower tail of the risk distribution fattened (no realized benefits from increased CO2 levels but an increased possibility of drought). The crop risk distribution is the distribution from which shocks to price and yield are generated in the simulation and can be altered by transforming the distributions used in the function estimate.m in the ALLEY Model 2.0 suite. The first group of simulated scenarios are those with the default (1%) tree catastrophe probability, while the second group of simulations are those with an increased (doubled to 2%) tree catastrophe probability. This was achieved by changing the variable pcatprob in the function params.m. Changing this parameter affects the mortality rate of timber products in the pine and alley crop systems. The following diagram illustrates the various simulations performed in this study. Each of the three scenarios in each group is described in more detail below.

4.2.1. Base case

The base case is the most simple test case for comparing monocrop, alley crop systems (24.4 m alleys), and traditional pine plantation. The parameters used in the base case are the defaults in Frey et al. (2018). To summarize, three commodity crops were allowed as options for planting each year, each of which has been historically planted in Halifax County, NC: corn, soybeans, and cotton. The 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 m × 3.05 m (8 ft. x 10 ft), the equivalent of 1345 trees per hectare (545 trees per acre). In the alley cropping model, the trees were spaced 2.44 m × 2.44 m (8 ft. x 8 ft) within double tree rows. The higher density of trees in the alley cropping system is due to the fact that trees only exist in the hedgerows and therefore do not compete for nutrients with other trees in all directions as is the case under a forestry regime. There were two alley width alternatives for the annual crop area: 24.4 m (80 ft) alley, the equivalent of 305 trees per hectare (124 trees per acre) overall; or a 12.2 m (40 ft) alley, the equivalent of 560 trees per hectare (227 trees per acre) overall. These two alley widths represent commonly used alley width in the region where the data for the simulations is obtained (McGraw et al., 2008).

4.2.2. Increased yield risk: two-sided

In this scenario, the standard deviation of crop yields was increased by 50%. This scenario is designed to investigate the impact that a relative increase in uncertainty across agricultural methodologies due to climate change will have on the financial viability of the studied land use models. Examples of future climate scenarios represented under this scenario include conditions combining elevated CO2 levels which contribute to increased photosynthesis rates (Makino and Mae, 1999) with a general trend of increased temperatures and altered rainfall patterns which have negative impacts on crop yields (Schlenker and Roberts, 2009).

4.2.3. Increased yield risk: lower tail only

This scenario is similar to the previous scenario with the difference that only the lower tails of the risk distributions are altered. This approach represents possible future climate scenarios in which temperature and rainfall changes affect crop yields negatively, but elevated CO2 levels do not offset these impacts on yields. To achieve this, the alpha parameter in the beta distribution (used to model yields) was altered to change the shape of the beta distribution itself. This scenario allows us to explore the financial viability of the studied agroforestry systems under a climate future in which agricultural production is threatened, i.e., a climate future in which any gains in agricultural production are more than offset by increased risks such as drought, excess heat, and hurricanes.

5. Results

Results for all the scenarios are reported in Table 2 and in Figs. 3 through 8. In Table 2, the mean SEV along with standard deviations for each scenario is provided. For all non-monocrop simulations, mean timber rotation lengths are included as well. Recall that the time horizon used in this model is 40 years for monocrop, and the length of the timber rotation (up to 40 years) for alley crop and pine systems. In Figs. 3 through 8 the CDFs of the SEVs for monocrop, alley crop, and pine plantation systems are compared. Figs. 3 through 5 compare the CDFs of the SEVs for the three different systems for the base case, two-sided increased yield risk, and an increased yield risk for the lower tail only. Figs. 6 through 8, which reflect a doubled catastrophe probability for the scenarios represented by Figs. 3 through 5, may be found in Appendix A.

As seen in Figs. 3 through 8, no land management regime is stochastically dominant when assessing SEV. Monocropping is preferable to both alley cropping and pine plantations on the higher end of the CDF. However, monocropping does not exhibit first order stochastic dominance as pine plantations represented the most preferable regime at the lower end of the CDF. This pattern held true in all six scenarios.

As expected, pine plantations offered the lowest expected value (mean) SEV but also the least risk (standard deviation) under every scenario, compared to monocropping and alley cropping. Mean SEV for pine plantations was approximately $2700 /ha for both the normal and doubled tree catastrophe probabilities. Standard deviations were approximately $1150 /ha. These results are based on average crop yields per hectare in Halifax County, NC. On more marginal agricultural land, however, it is possible that pine plantations might approach or surpass

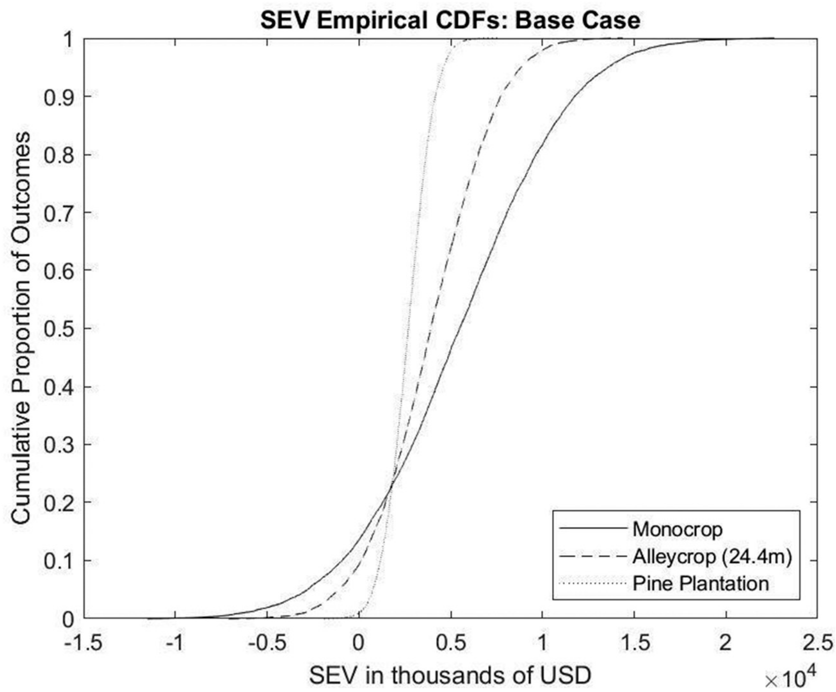

Fig. 3. Empirical CDFs for SEV for monocrop, alley crop, and pine plantations under the base case scenario.

the SEVs of agricultural and agroforestry systems.

In the base case, monocropping offered the greatest expected value (mean) SEV, at approximately $5500 /ha, with a standard deviation of approximately $5000 /ha. By comparison, alley cropping had expected value and standard deviation of SEV that were intermediate between monocropping and pine plantation (expected value approx. $4000 /ha and standard deviation approx. $3000 /ha). This is intuitive given that alley cropping combines aspects of monocropping and pine plantations on a single parcel of land. Still, it is important to note in Fig. 3, that monocropping is neither first nor second-order stochastically dominant over alley cropping. That is, the lower tail of the CDF of alley cropping SEV is to the right of the lower tail of the monocropping CDF, indicating less risk of the worst potential outcomes. This suggests that, even in the base case, some highly risk-averse farmers could still prefer alley cropping.

The increased two-tail scenario presented virtually no differences from the base case scenario. However, when the catastrophe probability was doubled under this scenario (see Fig. 7), the standard deviation of the simulated results actually decreased slightly. This is a consequence of the increased catastrophe probability disproportionately affecting returns from otherwise successful years. For years with simulated returns greater than the mean of the simulated returns in this scenario,

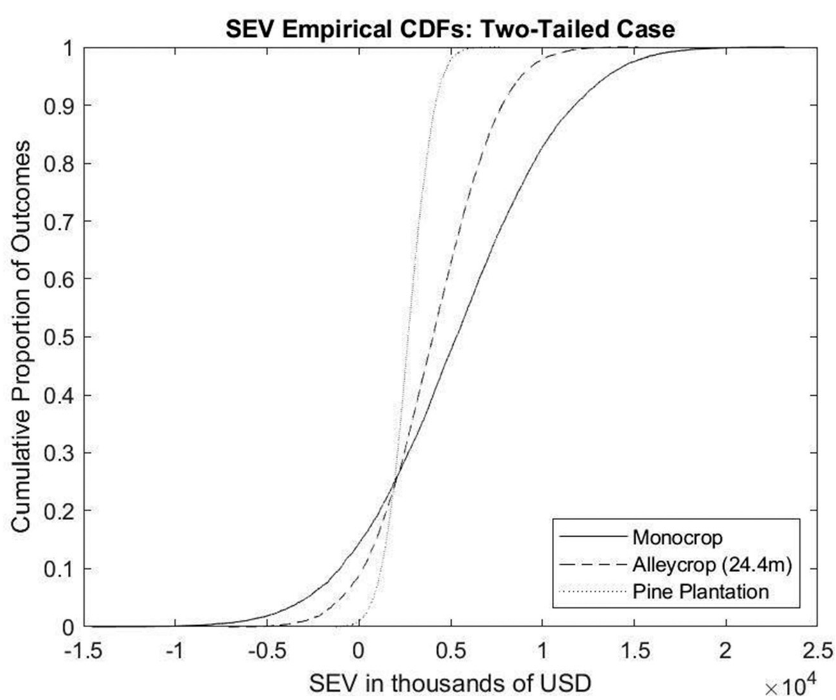

Fig. 4. Empirical CDFs for SEV for monocrop, alley crop, and pine plantations under the assumption of a general (two-tailed) risk increase.

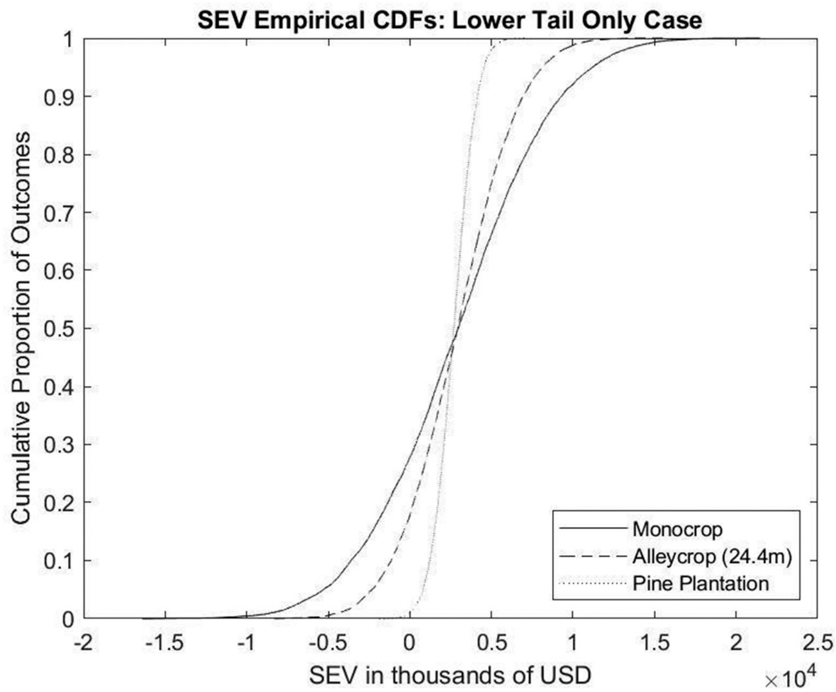

Fig. 5. Empirical CDFs for SEV for monocrop, alley crop, and pine plantations under the assumption of a fattened lower-tail.

foregone returns due to a catastrophe monotonically increase with the standard deviation of the simulated returns. Since the catastrophe probability was still relatively small (2%), mean returns were not significantly affected under this scenario.

The most drastic change in the comparison of returns between agroforestry systems came not from the increased probability of tree catastrophe, nor the two-tailed increased risk scenario, but from the scenario in which the lower tail of the yield distribution is flattened (Fig. 5). In fact, under this scenario, alley cropping offered expected value of SEV approximately equal to monocropping when the catastrophe probability was not increased. Without increasing tree catastrophe probability, the monocrop and alley crop expected value SEV were approximately $2900 / ha, although alley crop appeared slightly higher under these 10,000 iterations. Paired with the fact that the alley cropping has lower standard deviation of SEV (approx. $3100 /ha versus $4900 /ha for monocropping), alley cropping second-order stochastically dominates monocropping in this scenario. This means that a risk-averse farmer in this scenario would prefer alley cropping to monocropping. Generalizing these results, it appears that if yields are jeopardized under future climate scenarios, alley cropping under some plausible condition eventually surpasses monocropping as the preferred system from a financial perspective. For example, a *t*-test confirmed ($p < 0.001$) that there is a significant difference between the average SEV for monocropping between the base case and the scenario with the fattened lower tail (the difference in means between scenarios is 2601). This result holds true for both monocropping and alley cropping (though not for pine plantations) whether or not the catastrophe probability is doubled.

Table 2 also presents the average timber rotation length for the alley cropping and pine plantation systems. Timber rotations are determined in the ALLEY 2.0 Model post-hoc after modeling timber yields and prices out to 40 years, then evaluating each year to determine the harvest year that maximizes SEV (a discrete-time, post-hoc Faustmann approach). Due to random variability, each realization of the model may select a different optimal year. Because alley cropping SEV includes annual crop returns that decrease as trees grow due to competition, alley cropping optimal rotations were substantially shorter than those from pine plantation. The pine plantation optimal rotations were approximately 28 years on average, whereas alley cropping optimal rotations were approximately 20 years on average. The risk scenarios only changed optimal rotations for alley cropping modestly, from 20.0 years in the base case to 20.5 years in the increased lower-tail case. A t-test determined this change to be statistically significant ($p < 0.01$). Because that case includes more potential for poor annual crop returns, it makes intuitive sense that the optimal timber rotation might move closer to the length that generates higher timber returns, slightly de-emphasizing the importance of annual crop returns for alley cropping.

In Table 3, a comparison of how frequently particular crops are selected using the decision rule described above is presented. Neither crop selection frequencies nor average timber rotation lengths exhibit any noticeable changes due to changes in the tree catastrophe

Table 3
Percent of total years that each crop is selected.

	Corn (%)	Soybeans (%)	Cotton (%)
Base case			
Monocrop	21.027	39.288	**39.685**
Alley crop 24.4 m	19.480	**50.062**	30.458
Increased yield risk: two-tailed			
Monocrop	20.675	**39.730**	39.595
Alley crop 24.4 m	19.579	**50.220**	30.200
Increased yield risk: lower tail only			
Monocrop	20.974	38.685	**40.341**
Alley crop 24.4 m	19.621	**49.430**	30.949
Base case with increased catastrophe probability			
Monocrop	20.697	39.456	**39.847**
Alley crop 24.4 m	19.494	**50.047**	30.549
Increased yield risk: two-tailed with increased catastrophe probability			
Monocrop	20.798	39.512	**39.689**
Alley crop 24.4 m	19.521	**50.150**	30.329
Increased yield risk: lower tail only with increased catastrophe probability			
Monocrop	21.033	38.657	**40.310**
Alley crop 24.4 m	19.534	**49.348**	31.118

The boldened term in each row indicates the crop which was most often chosen by the model under the given regime.

probability.

6. Discussion

The results from the simulations provide unique insight into the potential consequences and benefits of alley cropping relative to monocropping, as well as into how the inherent flexibility of alley cropping responds to future climate scenarios.

In the simulations, alley cropping responded to the increased catastrophe probability models in part by increasing the average timber rotation length from approximately 20.0 years to 20.5 years. This is evidence of how alley cropping offers an advantageous flexibility in handling perceptions of risk and uncertainty. Since timber is the most risk averse land management strategy in the long run, alley cropping allows land managers the ability to update their expectations of future outcomes by extending or shortening the timber rotations. In the case of future climate scenarios with an increased probability of catastrophes such as fires, hurricanes, or pests, the simulations show that this risk aversion is expressed by extending timber rotations.

Given that the timber component of alley cropping is often used as an (often communal) investment in many parts of the world, increased timber rotation lengths for alley cropping under future climate scenarios will have an impact on livelihoods and community development in these areas.

Another important consequence of alley cropping highlighted in the simulations was its impact on crop selection. The significant increase in soybean production under alley cropping is a consequence of the competition between alley crops and hedgerow trees. The relative success of soybeans compared to cotton under alley cropping is a consequence of the fact that cotton is more dependent on sunlight, which is blocked by more mature trees, than soybeans (Frey et al., 2018). Given the magnitude of the impact observed in the simulations, this is evidence of a secondary impact of crop selection under alley cropping: its impact on market prices.

With increases in the adoption of alley cropping, changes in the supply of crops will ensue. As a consequence, markets will have to adjust, leading to new equilibria. This means that there will be changes in levels of demand and supply, as well as in prices. In developed economies this will be observed as further changes in crop selection to reflect the new equilibrium.

As far as alley cropping being a financially competitive alternative to monocropping, the simulations provide evidence of two key results. First, the simulations confirmed the existing literature which states that for sufficiently risk averse land managers, alley cropping is preferred over monocropping. Second, for possible future climate scenarios in which there is an increased catastrophe probability, alley cropping can compete with and possibly even out perform monocropping for risk neutral land managers.

7. Conclusions

The ALLEY 2.0 software suite was used to estimate profits under hypothetical future climate scenarios for alley cropping, monocrop, and pine plantations using historical data from Halifax County, North Carolina. This approach allowed farmers to switch annual crops to obtain better profits under stochastic, changing market conditions. Using this framework, returns for each system under several possible future climate scenarios were simulated. These scenarios included a base case, an assumption of a general (two-sided) increase in risk, and an assumption of increased risk in the form of a fattened lower tail in price and yield distributions. These scenarios were then re-run with a doubled (from 1% to 2%) probability of a major catastrophe (e.g., hurricane, fire, etc.) in any given year.

The simulations provided evidence of the impact of future climate scenarios on optimal timber rotations lengths and crop selection in alley cropping regimes. Timber rotations were lengthened on average when the catastrophe probability was increased as a response of alley cropping to the increased risk.

In term of the financial viability of alley cropping, it was determined that alley cropping as an agroforestry regime offers the highest NPV and SEV relative to monocropping under the worst-case scenario (i.e., when only the lower tails of the price and yield distributions were fattened). When risk was increased by increasing the variance of the entire distributions, alley cropping remained competitive with monocropping, offering similar NPV and SEV values to the base case. In the base case alley cropping offered the greatest SEV and trailed only monocropping in NPV. Pine plantations did minimize the risk as measured by the variance ratio. As a consequence of minimizing risk, no land management regime was stochastically dominant. These results are consistent with the theoretical models existing in the literature which indicate that integrated systems are more resilient that monocrop systems (Gil et al., 2017).

Disclaimers

The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

Use or description of any commercial product does not imply endorsement by the authors or their institutions.

Declaration of Competing Interest

The authors declare no conflicts of interest with the paper “Alley cropping as an alternative under changing climate and risk scenarios: A Monte-Carlo simulation approach”.

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Appendix A. Appendix

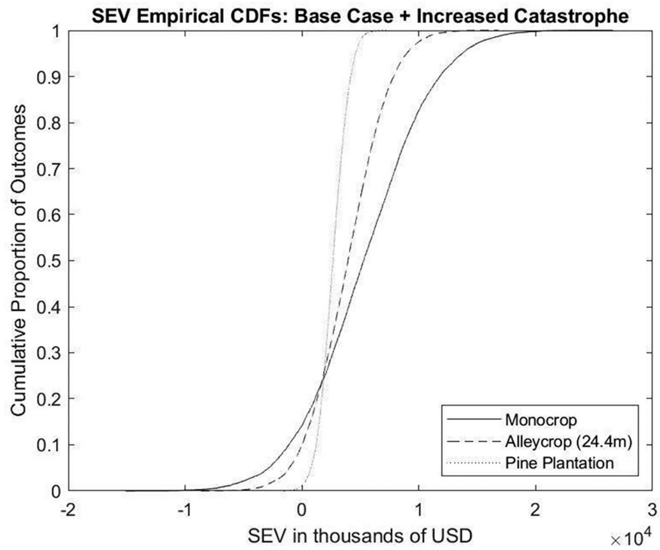

Fig. 6. Empirical CDFs for SEV for monocrop, alley crop, and pine plantations under the base case scenario with an increased catastrophe probability

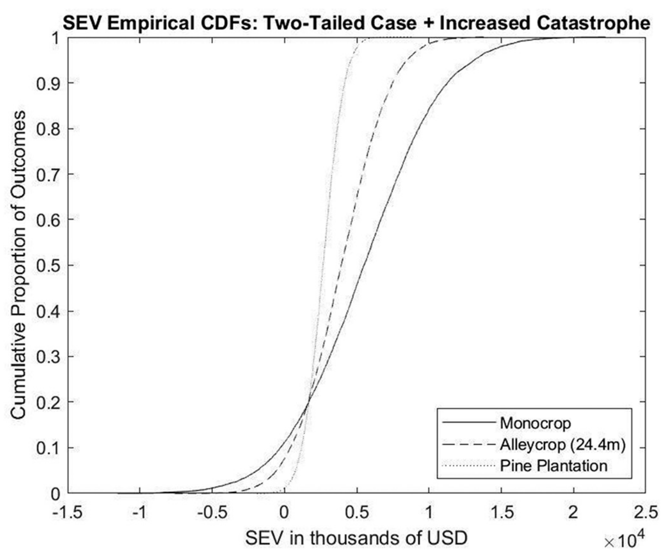

Fig. 7. Empirical CDFs for SEV for monocrop, alley crop, and pine plantations under the assumption of a general (two-tailed) risk increase with an increased catastrophe probability.

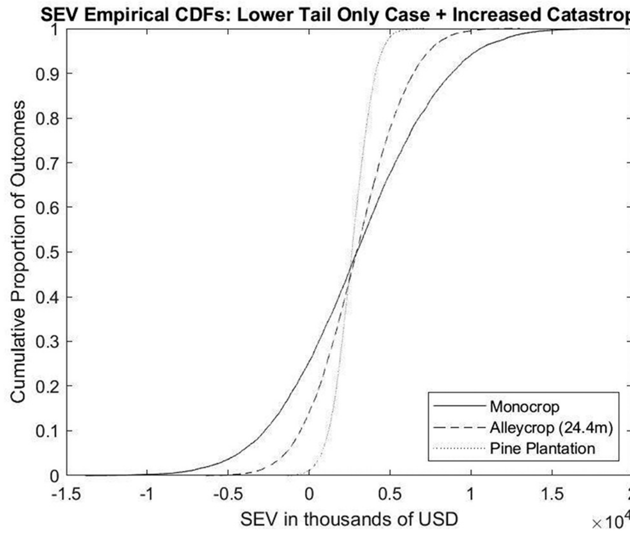

Fig. 8. Empirical CDFs for SEV for monocrop, alley crop, and pine plantations under the assumption of a fattened lower-tail with an increased catastrophe probability.

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