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Economics of intercropping loblolly pine and switchgrass for bioenergy markets in the southeastern United States

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Abstract The main objective of this study was to assess the economics of alley cropping of loblolly pine (*Pinus taeda* L.) and switchgrass (*Panicum virgatum*) in the southern United States. Assuming a price range of switchgrass between \$15 and \$50 Mg^{-1} and yield of 12 Mg ha^{-1} $year^{-1}$, we investigated the effect of switchgrass production on the optimal forest management for loblolly pine stands under different stumpage prices. We considered the following potential scenarios: no competition between species for resources; reduced loblolly pine productivity due to competition with switchgrass; and reduced productivity of both species due to competition for nutrients, water and light. Findings also suggested that the optimal system would depend on the competitive interactions between switchgrass and loblolly pine crops, and the expected prices for each crop. Loblolly pine monoculture would be the most profitable option for landowners compared to intercropping systems with switchgrass below \$30 Mg^{-1}. However, when switchgrass prices are $\geq$\$30 Mg^{-1}, landowners would be financially better off adopting intercropping if competitive interaction between crops were minimal. In order to realize higher economic returns for intercropping system, forest landowners must make some efforts in order to diminish the decline of productivity.

Keywords Bioenergy · Switchgrass · Loblolly pine · Alley cropping · Land expectation value

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Introduction

Alley cropping—in which agricultural crops are grown in the alleys between rows of trees—is an attractive option for forest landowners in a wide variety of productive sites in the southern US due to its potential environmental and economic benefits (Scott and Tiarks 2008; Zamora et al. 2009). Environmental benefits associated with alley cropping include improving the efficiency of nitrogen cycling and mitigating ground water contamination (Allen et al. 2004; Jose et al. 2004; Zamora et al. 2009). Potential economic benefits from alley cropping include increased economic returns, diversification of the outputs and shortened waiting times for income production (Zinkhan and Mercer 1997; Stainback and Alavalapati 2004).

Loblolly pine (*Pinus taeda* L.) is one of the most important commercial species in the southeastern US occupying more than 13 million ha (Schultz 1997 Jokela et al. 2004). It has been alley cropped with pasture (Burner 2003; Burner and Brauer 2003; Burner and MacKown 2005) and also with cotton (Zamora et al. 2009). Alley cropping aiming to produce biomass for bioenergy is also a potential option for forest landowners. For example, the 2008 farm bill provides incentives for farmers to grow cellulosic feedstock for bioenergy through annual payments for production and 75% of the cost of establishing perennial crops, site preparation, and tree planting for non-industrial private forestlands. Switchgrass (*Panicum virgatum*), a native perennial, warm season grass found commonly across the tall prairies of North America (Vogel et al. 2002), has been identified by the US Department of Energy Biomass Feedstock Development Program (DOE-BFDP) as one of the most promising bioenergy feedstock crops (Vogel 1996; McLaughlin and Kzos 2005).

Few studies have been conducted on intercropping loblolly pine with switchgrass. Weyerhaeuser and Chevron through the joint venture Catchlight Energy LLC are experimenting with intercropping loblolly pine with switchgrass in North Carolina (Chescheir et al. 2011). The Mississippi State University (Southeastern Sun Grant Center 2009) and the Louisiana State University AgCenter have also been studying the ecology and production of switchgrass in loblolly pine alleys (Blazier 2009). All of these studies are in their initial stages and the economic implications for landowners have not been widely investigated. The objective of this paper was to assess the economics of alley cropping of loblolly pine and switchgrass̄hereafter LP and SG, respectivelȳin terms of land values in the southern US We investigated the effect of SG production on the optimal forest management for LP stands considering the following potential scenarios: (1) no competition between species for resources, (2) reduced LP productivity due to competition with SG, and (3) reduced productivity of both species due to competition for nutrients, water and light.

The rest of this paper is organized as follows. In "Economic Model" section, we develop the economic model and its parameters, and discuss SG and LP growth and yield to assess the profitability of the alley cropping system. The assumptions of the competition scenarios and data are presented in "Data and scenario assumptions" section. The results are reported and discussed in "Results and discussion" section and conclusions in "Conclusions" section.

Economic model

Our economic model was based on the standard Faustmann approach that ascertains the profitability of forestlands in terms of the land expectation value (LEV) assuming forestry use in perpetuity. The LEV at time t is represented by:

$$LEV(t) = \frac{[PQ(t) - C(t)]e^{-rt}}{1 - e^{-rt}} \tag{1}$$

where P represents the price of the forest products, $Q(t)$ and $C(t)$ are the merchantable volume and costs associated with the establishment and management of the stand at time t, and r is the discount rate. The numerator in Eq. 1 represents the net present value for the first rotation of the stand. The denominator adjusts the expression to convert it to a perpetual time series. The time t that maximizes the LEV is the optimal rotation age. This optimization economic model can be extended to incorporate non timber products such as SG. In our study, P and $Q(t)$ represent a vector of prices and merchantable volume for sawtimber, chip and saw, pulpwood, and SG and $C(t)$ includes the costs associated with traditional forestry and SG production.

We employed a growth and yield model developed by the University of Georgia Plantation Research Management Cooperative (PRMC) (Harrison and

Borders 1996) to quantify the timber production of intensively managed, thinned LP stands:

$$Ln(Q) = -5.1759 + 0.1984Ln(N) + 1.2320Ln(H_d) + 0.7057Ln(BA) - 5.1298\frac{Ln(N)}{A} + 6.7314\frac{Ln(BA)}{A} \quad (2)$$

where Q is the total green weight outside bark in megagrams per acre (Mg $acre^{-1}$) at time t, N is the number of tree per acre, H_d is the average dominant height in feet, BA is the basal area in square feet per acre (ft^2 $acre^{-1}$) and A is the age of the stand in years. BA is defined as follows:

$$Ln(BA) = -\frac{42.6892}{A} + 0.3672Ln(N) + 0.6599Ln(H_d) + 2.0127\frac{Ln(N)}{A} + 7.7035\frac{Ln(H_d)}{A} \quad (3)$$

By inserting Eq. 3 into Eq. 2 we obtain the final expression for which is used to calculate the merchantable volume of LP stands. Thus:

$$Q_m = Qe\left[-1.0344\left(\frac{l}{d_q}\right)^{3.9498} - 5.0629N^{-0.4228}\left(\frac{d}{d_q}\right)^{6.0046}\right] \quad (4)$$

where Q_m is merchantable volume in cubic feet per acre (ft^3 $acre^{-1}$) for trees with a diameter breast height equal or greater than d inches to top diameter of l inches outside bark and d_q is the quadratic mean diameter in inches. The merchantable volume function and its parameters were converted to cubic meter per hectare (m^3 ha^{-1}) and to centimeters (cm) for the economic analysis.

With the exception of Environmental Policy Integrated Climate model (EPIC) (Thomson et al. 2009) and (Wullscheleger et al. 2010) that simulate growth and yield for SG, analyses of biomass yield data have been obtained through empirical experiments. Wide ranges of SG yields have been reported in the literature depending on the geographic region (Parrish and Fike 2005). Fike et al. (2006) reported average yields of 12.6 and 15.8 Mg ha^{-1} on dry basis for upland and lowland cultivars, respectively, in the southeastern US. Other estimates have ranged between 10 and 17 Mg ha^{-1} (McLaughlin and Kzos 2005), 7.7 and 15 Mg ha^{-1} (Cassida et al. 2005), and 8 and 17 Mg ha^{-1} (Mooney et al. 2009). A typical issue for forest landowners who are considering intercropping is the low productivity of the crop (Zinkhan and Mercer 1997). Our simulations were based on a yield of 12 dry Mg ha^{-1} $year^{-1}$, a plausible average estimate for the southern US.

We also estimated the economics of SG monoculture determining the present value (PV) of a perpetual periodic series:

$$PV = \frac{W}{e^{rp} - 1} \quad (5)$$

where W represents the net revenues due to SG production at the end of the period p. Once established, SG can persist indefinitely although replanting every 9–10 years is suggested (Perrin et al. 2008). For simulation purposes we have considered annual production of SG production for a period of 9 years before replanting.

Data and scenario assumptions

The forest products dimensions were defined as l = 17.8 cm and d = 29.2 cm for sawtimber, l = 15.2 cm and d = 19 cm for chip and saw, and l = 7.6 cm and d = 11.4 cm for pulpwood. Site index at a base of 25 years was assumed to be 20 m. Loblolly spacing and distance between rows were assumed to be 1.5 and 6 m, respectively, resulting in a stocking density of 1,077 trees ha^{-1}. Considering the inherent difficulties in SG establishment, we assumed that SG was planted at the same time as LP in a 3 m strip between rows leaving a 1.5 foot buffer area to each side to minimize competition between LP and SG.[1] Thus, half of the land in the intercropping system was allocated for SG production.

[1] SG may also be planted before planting trees to ensure its successful establishment. However, tree planting should not be delayed more than 1 year since SG production may be large and become a competitive challenge for the establishment of LP (Scott Roberts, Department of Forestry, Mississippi State University, March 10th 2011, personal communication). Conversely, delaying SG establishment after trees are planted may not be logistically feasible (Thomas Fox, Department of Forest Resources and Environmental Conservation, Virginia Polytechnic Institute and State University, March 14th 2011, personal communication)

Intercropping LP and SG may affect the productivity of both species due to competition for water, nutrients and light (Zhao et al. 2008; Jokela et al. 2010). Some evidence on the effect of SG as an invasive weed on LP productivity exists in the literature. For example, LP production doubled in stands with weed control treatments (Neary et al. 1990; Haywood et al. 1997). Shade can also reduce the production of SG. Lin et al. (1999) found decreases in SG yield by 28 and 66% with 50 and 80% shade, respectively. However, competition for light in the alley crop can be managed through the design of the alley cropping system (Jose et al. 2004). In our analysis, full productivity of the SG stand was assumed to occur 3 years after planting following literature such as McLaughlin and Kzos (2005) and Parrish and Fike (2009), attaining rates of 33–66% of its maximum production at years 1 and 2, respectively. We also accounted for reduced SG production at the time of LP canopy closure which occurs around the eighth year (Dickens et al. 2007) or later (Radtke 1996; Svensson et al. 1999; Adams et al. 2008). In our analysis, production of SG was assumed to extend year 9.

We defined six scenarios to account for potential competition between LP and SG. Scenario A assumed a LP monoculture (baseline scenario). In scenario B, LP was intercropped with SG but there was no competition between SG and LP for nutrients, water and light and no reduction in productivity of either species. In scenario C, LP was the predominant species and reduces SG productivity by 15% starting from year 3 throughout the last harvest of SG. In scenario D, LP and SG strongly competed for resources at early stages causing a reduction in SG and LP productivity by 15%, until the end of their respective rotation ages. Similarly, in Scenario E, LP and SG competed for resources increasing the reduction in SG and LP productivity by 15 and 25%, respectively. Scenario F assumed a SG monoculture. The economic model specified earlier was applied to each scenario to estimate the land values of the intercropping stand and the optimal rotation ages.

We also investigated the effect of increasing tree density and SG planted area on the profitability of the intercropped system. Distance between planted pine rows was reduced to 4.5 m increasing stock density to 1,435 trees ha^{-1} and maintaining the same width of the SG planted area. As a result of increased tree density, the area planted with SG also increased to 66% per acre. Under these new silvicultural conditions we would expect increased competition for nutrients, water and light. Thus the same scenarios defined earlier were simulated adding decreases in SG productivity by 50% (Scenario C_1), and decreases in SG and LP productivity by 50 and 35% (Scenario E_1).

The thinning schedules were determined based on a percentage range of the maximum Reinecke' stand density index[2] (SDI) (Reineke 1933) which requires maintaining adequate site occupancy (lower growing stock limit), and to avoid density–mortality related and to maintain individual tree vigor (upper growing stock limit) (Dean and Jokela 1992; Dean and Baldwin 1993). In the case of LP, lower and upper stocking limits can be set at 30 and 50% of the maximum SDI, respectively (Dean and Baldwin 1993). Greater percentage ranges—around 35–60% of the maximum SDI—can be employed since they have empirically allowed for god tree selection opportunities and a practical level of harvest for loblolly pine in the southeastern US (Marshall Jacobson, Plum Creek Timber Company, November 2nd 2011, personal communication).

Selecting a percentage between those ranges allows for determining the thinning schedule based on the conditions of the stand rather than fixing a particular age. We set a cutoff limit of achievement of 55% of the maximum SDI to determine the thinning schedules. Following this percentage two commercial thinnings were timed at ages 11 and 16 years for the stand with SI = 1,077 trees ha^{-1}. Each thinning intensity removal was set at 33% of the living trees.

Earlier thinnings might also be scheduled in case of increased tree density as competition for resources would also start earlier (Barron-Gafford et al. 2003). Given the SDI approach, the thinnings were scheduled at ages 10 and 15 years for the stand with SI = 1,435 trees ha^{-1}. However, we decided to maintain the original thinning timings (11 and 16 years) for the increased tree density scenario. This was undertaken in order to compare across both stand density scenarios by isolating the economic effects of bringing forward the thinning age on the profitability of the

[2] $SDI = Tpha\left(\frac{d_q}{25.4}\right)^{1.605}$ where $Tpha$ is trees ha^{-1} and is the quadratic mean diameter (cm). For LP the maximum SDI = 1140 (Zeide and Stephens 2010).

forest/intercropping stand. Our chosen thinning schedules are well within the range reported for loblolly pine in the southeastern US (Gonzalez-Benecke et al. 2011).

The Faustmann approach used in our analysis is based on the assumption that stumpage prices remain constant over time. Stumpage prices might also vary over time following a stochastic process (Lohmander 2000; Gong and Lofgren 2007). For example, sawtimber and chip and saw, have declined since mid-2000s, and are currently at historically low levels in the southeastern US (Timber Mart South 2006; Timber Mart South 2010). Stochastic methods such as the reservation price approach (Lu and Gong 2003) and the option pricing approach (Thomson 1992) have been developed to capture the uncertainty of stumpage prices. However, the use of these approaches would imply to ascertain the type stochastic process (stationary, non stationary or diffusion process) for stumpage prices and SG prices which is beyond the scope of our paper. Furthermore, limited the information about the effect of SG prices on forest product prices is currently unknown due to lack of historical prices of SG.

The evolving stumpage prices have been included in our analysis by modeling three categories of stumpage prices considering the period between 1994 and 2011. Following this approach, we captured a variety of scenarios to reflect past and current market price levels in the southern US based on historical records (Timber Mart South 2006; Timber Mart South 2010). The three categories were as follows: price of sawtimber, chip and saw and pulpwood of \$48, \$28, and \$12 m^{-3}, respectively (high stumpage prices), \$36, \$22, and \$10 m^{-3} (medium stumpage prices), and \$31, \$19, and \$8 m^{-3} (low stumpage prices), respectively. All nominal prices were deflated (base year 2010) by using the Producer Price Index for lumber and wood products provided by the United States Department of Labor Bureau of Labor Statistics (2011).

Setting a potential competitive price for SG is complex since the current market for SG in bioenergy production is essentially non-existent, i.e., current price of SG is zero. Reported potential competitive prices of SG for bioenergy production range between \$40 and \$70 Mg^{-1}, on dry basis (Mitchell et al. 2008; Mooney et al. 2009; Perrin et al. 2008). McLaughlin et al. (2002) and McLaughlin and Kzos (2005) established a SG price of \$44 Mg^{-1} under the rationale that it would generate greater economic returns for switchgrass production than other traditional crops on 17 million ha in the US. Furthermore, at this price level, 5.3 million ha of conservation reserve program lands could be converted to switchgrass and maintain the same environmental market benefits such as carbon soil sequestration and carbon emission reduction (McLaughlin et al. 2002). To cover the possible spectrum of SG prices assuming that the market for this bioenergy resource would become stronger over time, we considered the following expected SG prices: \$15, \$30, \$44, and \$50 Mg^{-1}. The discount rate was set to 4%.

Costs associated with the establishment and development of LP stands were based on Smidt et al. (2005), Fox et al. (2007), and Peter et al. (2007), to be: \$199 and \$78 $acre^{-1}$ for site preparation (shear, rake, pile and bed) and aerial weed control before establishment, respectively. Planting cost and seedling cost were \$0.085 $plant^{-1}$ and \$0.05 $seedling^{-1}$. Band weed control cost was \$93 ha^{-1} at year 1 and fertilization costs were \$222 ha^{-1} at year 5, 11, and 16. A marking cost of \$35 ha^{-1} was assumed at the age of thinnings and yearly management costs were set to \$15 ha^{-1}. Costs associated with SG production were procured from University of Tennessee Institute of Agriculture (University of Tennessee- Institute of Agriculture 2009). Establishment cost (seed, fertilizer, weed control and machinery) was assumed to be \$444 ha^{-1}. Weed control of \$32 ha^{-1} was considered including broadleaf and grass herbicide post emergence (year 1). Annual fertilization cost was set to \$113 ha^{-1}. Annual management cost for the intercropping system was assumed to be \$15 ha^{-1}. We assumed the same costs associated with SG production over subsequent growing cycles given the assumption of a perpetual periodic series for this monoculture.

Results and discussion

Tables 1 and 2 show the profitability of the LP and SG monoculture, and intercropping system based on the LEVs (\$ ha^{-1}), and optimal rotation ages (years), respectively, for the different combinations of LP stumpage prices and SG prices, under the different productivity scenarios. The optimal system depended on the expected prices for SG and stumpage prices for

Table 1 Land expectation value (LEV) for LP, SG and intercropping system for different productivity-price scenarios and stand density = 1,077 trees ha^{-1}

Scenario	Definition	SG price ($ Mg^{-1})	Stumpage price ($ m^{-3})		
			High LEV ($ ha^{-1})	Medium	High
Scenario A	No intercropping	n.a	6888.88	4659.3	3589.44
Scenario B	No decrease in SG or LP productivity	15	6686.9	4457.5	3387.6
		30	7708.5	5479.0	4409.1
		44	8662.9	6440.5	5364.7
		50	9084.6	6862.2	5786.4
Scenario C	15% decrease in SG productivity	15	6555.7	4326.2	3259.7
		30	7446.0	5216.5	4146.6
		44	8277.0	6047.5	4977.6
		50	8633.1	6410.8	5335.0
Scenario D	15% decrease in SG and LP productivity	15	5365.2	3418.8	2486.0
		30	6255.5	4309.2	3366.7
		44	7086.5	5140.1	4197.6
		50	7447.8	5505.8	4557.3
Scenario E	15% decrease in SG and 25% decrease in LP productivity	15	4571.6	2815.6	1970.3
		30	5461.9	3704.2	2846.7
		44	6292.8	4535.2	3677.6
		50	6657.5	4902.5	4038.8
Scenario F[a]	SG monoculture	15	−427.9		
		30	2891.1		
		44	5988.8		
		50	7316.4		

[a] Stumpage prices are not applicable to Scenario F

LP, and the competitive interaction between the crops in the intercropping system.

Land expectation values of the intercropping systems were reduced as competition between the two crops increased for the same stumpage prices. As expected, the profitability of intercropping changed in the same direction as the change in the prices of SG and LP. For the same level of competitive interaction between the crops, the profitability of the monoculture/intercropping system decreased as SG/LP stumpage prices decreased. Additional decreases in the productivity of either SG or LP (Scenarios C, D, and E) caused a decrease in the land values of the intercropping system for the same level of stumpage prices, compared to no decrease in SG or LP productivity scenario (Scenario B).

Results suggested that traditional forestry (Scenario A) with high stumpage prices generated higher land values than all intercropping scenarios when the expected price for SG was $15 Mg^{-1}. Similarly, with medium and low stumpage prices, the profitability of forestry monoculture was higher than the profitability of intercropping scenarios for the lowest SG price level, respectively. For expected SG prices equal and above $30 Mg^{-1}, the profitability of intercropping with high stumpage prices was greater than revenues generated by traditional forestry with any level of stumpage prices, under no decrease in LP and SG productivity scenario (Scenario B) and 15% decrease in SG productivity scenario (Scenario C). For the same scenarios (B and C) and range price for SG (equal and above 30 Mg ha^{-1}), higher land values were realized for the intercropping system compared to those for LP monoculture, with medium and low stumpage prices, respectively. For the same scenarios (B and C) and with expected SG prices equal and above $44 Mg^{-1} and low stumpage prices, higher intercropping land values were obtained than forestry monoculture land values with medium stumpage prices.

In the scenario with a loss of 15% productivity of SG and LP (Scenario D), the profitability of intercropping were higher than those of LP monoculture

Table 2 Optimal rotation age (RA) for LP, SG and intercropping system for different productivity-price scenarios and stand density = 1,077 trees ha^{-1}

Scenario	SG price ($ Mg^{-1})	Stumpage price ($ m^{-3})		
		High RA (years)	Medium RA (years)	Low RA (years)
Scenario A	n.a	21	21	21
Scenario B	15	21	21	21
	30	21	21	21
	44	20	20	20
	50	20	20	20
Scenario C	15	21	21	21
	30	21	21	21
	44	20	20	20
	50	20	20	20
Scenario D	15	21	21	22
	30	21	21	21
	44	20	20	20
	50	20	20	20
Scenario E	15	21	21	22
	30	21	21	21
	44	20	20	20
	50	20	20	20
Scenario F	15	9		
	30			
	44			
	50			

(Scenario A) with high, medium and low stumpage prices, respectively, in case where the expected price of SG was equal or higher than $44 Mg^{-1}. In the scenario, where productivity of SG and LP decreased by 15 and 25% respectively (Scenario E), intercropping was not an economically superior option for landowners compared to traditional forestry with high stumpage prices. With medium stumpage prices, landowners would be economically better off with the intercropping system if the expected SG price were $50 Mg^{-1}. Intercropping land values were higher with expected SG prices equal or above $44 Mg^{-1} than those for LP with low stumpage values.

For Scenarios D and E, intercropping systems with high stumpage prices realized higher returns than LP land values with medium stumpage prices (expected SG prices between $15 and $50 Mg^{-1} and $30 and $50 Mg^{-1}, respectively). For the same scenarios and with expected price range for SG between $30 and $50 Mg^{-1}, intercropping systems with medium stumpage prices generated higher land values than those for LP with low stumpage prices.

Devoting land for SG monoculture (Scenario F) would provide greater economic returns with high expected SG prices of $44–$50 Mg^{-1} than forestry monoculture only in case of medium and high stumpage prices, respectively. SG monoculture with an expected SG price of $50 Mg^{-1} would be a financially better option for landowners compared to intercropping systems with decrease in productivity of SG and LP (Scenarios D and E) at any stumpage price level— with the exception of the land value given by high stumpage prices and expected SG price of $50 Mg^{-1} for Scenario D. Likewise, SG monoculture with an expected SG price of $50 Mg^{-1} generated higher economic returns compared to intercropping systems with decrease in productivity of SG (Scenario C) with medium and low stumpage prices. With exception of the following combinations: medium stumpage prices and lowest expected SG price for Scenario E, low stumpage prices and price range for SG between $15 and $30 Mg^{-1} for Scenario E, and low stumpage prices and lowest SG price for Scenario D, intercropping systems came out as an economically superior option for landowners for all scenarios compared to SG monoculture.

The optimal rotation age was only 1 year longer for traditional forestry than any of the intercropping systems scenarios in case of highest expected price level for SG—$50 Mg^{-1}. High economic revenues realized due to SG production in the early years of the rotation, in turn incentivizing forest landowners to harvest and replant trees earlier relative to traditional forestry. Similar finding of intercropping longleaf pine and pasture were found by Stainback and Alavalapati (2004).

Tables 3 and 4, respectively, show the effect of increased tree density and SG planted area on the profitability of the different systems and optimal rotation age for all scenarios. Increased tree density had a minimal impact on profitability of traditional forestry. On average, the reduction of land values was nominal (2.1%) for all level of stumpage prices. In general, increased tree density caused an increase in the land values compared to those for the same scenarios under the initial tree density and SG planted

Table 3 Land expectation value (LEV) for LP and intercropping system for different productivity-price scenarios and stand density = 1,435 trees ha^{-1}

Scenario	Definition	SG price ($ Mg^{-1})	Stumpage price ($ m^{-3})		
			High LEV ($ ha^{-1})	Medium	Low
Scenario A	No intercropping	n.a	6736.55	4572.0	3504.3
Scenario B	No decrease in SG or LP productivity	15	6567.5	4403.0	3335.3
		30	7920.5	5752.5	4673.5
		44	9191.8	7023.7	5944.8
		50	9736.6	7583.8	6502.3
Scenario C	15% decrease in SG productivity	15	6397.6	4233.1	3165.4
		30	7570.6	5402.5	4323.6
		44	8678.6	6510.5	5431.5
		50	9153.4	6985.3	5906.4
Scenario C_1	50% decrease in SG productivity	15	6001.2	3836.7	2769.0
		30	6757.5	4593.0	3525.3
		44	7481.0	5312.9	4234.0
		50	7792.5	5624.5	4545.5
Scenario D	15% decrease in SG and LP productivity	15	5214.6	3327.9	2387.7
		30	6384.7	4493.5	3542.8
		44	7492.6	5601.5	4650.8
		50	7967.4	6079.7	5125.7
Scenario E	15% and 25% decrease in SG and LP productivity	15	4425.8	2724.3	1869.2
		30	5594.0	3887.5	3022.4
		44	6702.0	4995.5	4130.3
		50	7176.8	5478.1	4609.3
Scenario E_1	30% and 35% decrease in SG and LP productivity	15	4122.5	1950.9	1188.2
		30	4453.5	2933.8	2163.7
		44	5398.1	3876.2	3096.6
		50	5802.9	4281.1	3501.4

area reported in Table 1. On average, for all combinations of stumpage prices and SG prices, higher revenues (5.4, 4.1, 4.8 and 5.4%) were realized for Scenarios B, C, D and E, respectively, in case of new stand density conditions, compared to the same scenarios described in Table 1.

These higher land expectation values could result from the effect of different silvicultural operation and treatments on the intercropping stand. Higher tree density increased the proportion of pulpwood and chip and saw at lower prices offsetting the loss in the proportion of sawtimber at a higher price. Furthermore, silvicultural treatments such as weed control and fertilizations typically enhance forest growth (Jokela et al. 2004). For example, assuming no decrease in the productivity of the intercropping system, the effect of weed control and fertilizations generated, on average, 9–38% more chip and saw and pulpwood between ages 10 and 20 years for the stand with higher tree density. Revenues from thinnings—mainly pulpwood and chip and saw—were 44% greater for the increased tree density scenario. Finally, increased tree density allowed for an increase in 33% of the SG productivity generating higher economic revenues. Thinnings did not have effect on the SG productivity since they were scheduled later than the assumed life cycle of SG (age 9 years).

Consistent with expectations, decreases in the profitability of intercropping systems were accentuated with higher reductions of the productivity of SG and both crops under the new stand density. The reduction of land values for Scenario C_1 and E_1 was 15 and 23%, respectively, compared to the land values for Scenarios C and E. Thus, landowners should focus

Table 4 Optimal rotation age (RA) for LP and intercropping system for different productivity-price scenarios and stand density = 1,435 trees ha^{-1}

Scenario	Definition	SG price ($ Mg^{-1})	Stumpage price ($ m^{-3})		
			High RA (years)	Medium RA (years)	Low RA (years)
Scenario A	No intercropping	n.a	21	21	22
Scenario B	No decrease in SG or LP productivity	15	21	21	22
		30	21	21	21
		44	20	20	20
		50	20	20	20
Scenario C	15% decrease in SG productivity	15	21	21	22
		30	21	21	21
		44	21	20	20
		50	20	20	20
Scenario C_1	50% decrease in SG productivity	15	22	22	22
		30	21	21	22
		44	21	21	21
		50	21	21	21
Scenario D	15% decrease in SG and LP productivity	15	22	22	22
		30	21	21	21
		44	20	20	20
		50	20	20	20
Scenario E	15 and 25% decrease in SG and LP productivity	15	22	22	22
		30	21	21	21
		44	20	20	20
		50	20	20	20
Scenario E_1	30 and 35% decrease in SG and LP productivity	15	22	22	23
		30	21	21	22
		44	21	20	21
		50	20	20	20

their efforts on implementing management practices such as fertilization, weed control, and planting genetically improved seedlings of LP and SG to increase the overall productivity of the site.

On average and for all combinations of stumpage process and SG prices, a 50% loss of the productivity of SG (Scenario C_1) caused a profitability reduction of 13 and 12% in the intercropping system vis-a-vis to the profitability with initial stand conditions for Scenarios B and C, respectively. Higher reductions of the productivity in intercropping systems implied a higher decrease in the profitability of the intercropping systems. The profitability for Scenario E_1 decreased by 44, 29, and 19%, respectively, compared to the profitability for Scenario B (no reduction in productivity), D (15% reduction in productivity for both crops), and E (15 and 25% reduction in productivity for SG and LP, respectively) with initial stand density assumptions.

Traditional monoculture forestry was economically a better option compared to those intercropping system scenarios in which competition between the crops resulted in large decreases in the productivity for both species (Scenario E_1). Similar to the original stand density assumptions, at expected SG prices of $44–$50 Mg^{-1}, landowners could be financially better off planting SG compared to traditional forestry with increased tree density. For the same expected price, SG monoculture would continue being a more profitable option for landowners compared to the intercropping systems with high decreases in overall productivity due to competition (Scenario E_1), moderate decrease in overall productivity with medium and low stumpage prices (Scenario D—with the exception of the combination of medium stumpage prices and highest SG price—and Scenario E), and high decrease only in SG productivity with medium and low stumpage prices (Scenario C_1). Likewise, SG monoculture with an expected price of \$50 Mg^{-1} would be a financially superior option for landowners compared to the systems with low decrease in SG productivity with medium and low stumpage prices (Scenario C) and no change in overall productivity of the stand with low stumpage prices (Scenario B).

Conclusions

The implications of intercropping LP and SG on the profitability of forestlands were analyzed in this study. As expected, increased competition between the two crops, low stumpage and SG prices would reduce the profitability of the intercropping system. Findings also suggested that the optimal system would depend on the competitive interactions between SG and LP crops, and the expected prices for SG and LP.

LP monoculture would be the most profitable option for landowners compared to intercropping systems with low prices for SG (below \$30 Mg^{-1}). When SG prices exceed \$30 Mg^{-1}, landowners would be financially better of adopting intercropping system with any level of stumpage prices if competitive interaction between crops were minimal. This might be particularly beneficial for landowners who want to improve their competitiveness and aim towards diversifying their management options in light of bioenergy markets. However, with higher decreases in the productivity of the intercropping system, traditional forestry with high stumpage prices would provide higher financial benefit for landowners. If stumpage and SG prices remained at a relatively medium and high level, intercropping systems would be a preferable option. On the other hand, devoting land for SG monoculture with relatively high expected SG prices would be the superior option for landowners compared to traditional forestry. In addition, SG monoculture with high expected SG prices would the most profitable option compared to intercropping systems with high competition for resources. In order to realize higher economic returns for intercropping system, forest landowners must make some efforts in order to diminish check the decline of productivity.

Increased stock density and area planted with SG through shortening planting distance between pine planting rows increased the profitability of the intercropping system. However, with a strong reduction of the productivity of SG and LP, the profitability of the intercropping systems abruptly fell compared to the economic revenues obtained in case where there was no loss of productivity and the initial stand management assumptions were maintained. Similar to the initial forest stand management, landowners should adopt SG monoculture with high SG prices instead of traditional forestry, under increased tree density conditions. Likewise, landowners would be financially better off in case of traditional forestry and SG monoculture than intercropping systems when competition between the crops resulted in large decreases in the productivity of LP and SG.

A limitation of our study was the deterministic feature of our economic model. Volatile stumpage prices reflect the uncertainty of forest product markets (Mei et al. 2009) and the development of switchgrass development is currently at early stages. Therefore, as switchgrass prices evolve, the use of other methods that incorporate uncertainty such as autoregressive models or Montecarlo simulations may be required. Improvement of current policies aiming to favor the conditions for the development of SG based bioenergy markets and stumpage markets might be required.

Further silvicultural efforts might be focused on testing suitable stock density, and rates of fertilization and weed control. Development of growth and yield functions of SG may be necessary to evaluate intercropping systems in face of growing demand for biofuels, and to determine the optimal productivity and price levels of the alley cropping system. Also, internalization of environmental benefits such as carbon sequestration and implications on the intercropping management may be an additional research to our study.

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