ASSESSING ECONOMICS AND ENVIRONMENTAL FEASIBILITY OF INTERCROPPING LOBLOLLY PINE AND OILSEED CROPS FOR BIO-JET FUEL PRODUCTION IN THE SOUTHERN UNITED STATES

by

HOSNE ARA AKTER

(Under the Direction of Puneet Dwivedi)

ABSTRACT

Reforested hectares of loblolly pine (*Pinus taeda* L.) plantation could be used for intercropping oilseed crops such as carinata (*Brassica carinata*) and white lupin (*Lupinus albus* L.) for producing bio-jet fuel to reduce carbon emissions of the aviation sector. Intercropping remained profitable unless the productivity of all three species reduced by a higher percentage. The probability of loss related to the intercropping production systems increased with a decrease in yields. Seed yield of carinata and interest rate had the most significant positive and negative impact, respectively, on the profitability of intercropping. Intercropping loblolly pine with carinata decreased the total aboveground carbon storage by 14.24 t, 6.51 t, and 4.71 t C/ha than loblolly pine only management scenario for site indices 21.3m, 18.3m, and 15.3m, respectively over 100-years planning period. Overall, intercropping would increase the profitability of landowners but decrease the carbon storage relative to the loblolly pine only production system.

INDEX KEYWORDS: Aviation Sector, Bio-jet fuel, Carbon in Wood Products and Landfills, Climate Change, Forest Management, Forest Sustainability

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DEDICATION

I dedicate this thesis to my mother, Safia Begum.

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CHAPTER 1

ECONOMICS OF INTERCROPPING LOBLOLLY PINE AND OILSEED CROPS FOR BIO-JET FUEL PRODUCTION IN THE SOUTHERN UNITED STATES[1]

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[1] Akter, H.A., Dwivedi, P., Anderson, W. & Lamb, M. Submitted to *Agroforestry Systems*, January 19, 2020.

Abstract

Currently, there are 13.9 million ha of loblolly pine (*Pinus taeda* L.) in the southern United States. Reforested hectares could be used for intercropping oilseed crops such as carinata (*Brassica carinata*) and white lupin (*Lupinus albus* L.) before the canopy closure. The oil obtained from these oilseed crops could be used for bio-jet fuel production to reduce the carbon footprint of the aviation sector. This study determines the profitability for three scenarios: loblolly pine with no intercropping (baseline), loblolly pine with carinata (once every three years), and loblolly pine with carinata and white lupin rotated annually. We ascertained the land expectation value (LEV) for three site indices of 15.3m, 18.3m, and 21.3m. Carinata and white lupin were planted during the initial eight, seven, and six years for site indices 15.3m, 18.3m, and 21.3m, respectively. Sensitivity and risk analyses were undertaken for determining the influence of input variables on the LEVs and the probability of loss for intercropping production systems relative to a baseline production system, respectively. For site index 21.3m, the LEV of loblolly pine with no intercropping was $3188/ha at a 21-years rotation period. Intercropping with carinata only and both carinata and white lupin yielded LEVs of $3674/ha and $3935/ha at a 21-years rotation period, respectively. The LEVs of production systems were sensitive to interest rate and price and yield of carinata seeds. The probability of loss related to the intercropping production systems increased with a decrease in yields. Future research should focus on the impacts of intercropping on the loblolly pine yield and adoption behavior of forest landowners.

Introduction

At present, the global jet fuel demand is about 8% of the total refined petroleum product demand of 7.43 million barrels/day, and the percentage is expected to rise to about 10% by 2040

(Vertz and Sayal, 2018). The consumption of petroleum-based jet fuel is a significant source of greenhouse gas emissions. The commercial aviation industry is currently responsible for about 2% of the total carbon emissions (Air Transport Action Group, 2011). However, as per the Intergovernmental Panel on Climate Change, the percentage is expected to rise to 15% of global carbon emissions by the end of 2050 due to increased air travel demand (Michailos, 2017). Based on the current estimates, the carbon dioxide emissions will reach 43 Gt by 2050 if no immediate steps are taken to mitigate greenhouse gas emissions in the aviation sector (Pardee, 2015).

Concerned by the current situation, the International Air Transport Association set a target of reducing carbon emissions to 50% by 2050 (the base year 2005) and stabilizing carbon emissions at 2020 level to achieve carbon-neutral growth through the adoption of Carbon Offsetting and Reduction Scheme for International Aviation (IATA, 2018). It is stated that 1,039 Mt of carbon dioxide emissions must be mitigated by the end of 2050 for ensuring the carbon-neutral growth of the aviation sector (ICAO, 2016).

Of several options available for reducing carbon emissions in the aviation sector, jet fuel derived from biomass is a promising one. Several studies have analyzed the economics of jet fuel derived from several feedstocks (Table 1.1). They have found that the unit production cost of bio-jet fuel ranges from US $ -0.22/l and US $2.78/l depending upon feedstock type, yield, capital cost, co-product credit, discount rate, oil content, and plant capacity. A closer look at the existing studies suggests that the majority of studies have analyzed carbon benefits and the economics of bio-jet fuels obtained from agriculture-based feedstocks. Intercropping, a production practice of planting crops in the alley between rows of trees (Kemp, 2011), could help in meeting the demand for bio-jet fuel feedstock. This is especially true in the context of the Southern United States, where on average, about 0.81 million hectares of forestland are planted each year, and about 86% of total forestland is under private ownership (Oswalt et al., 2019). Therefore, intercropping could be an attractive option for landowners to manage their land resources more efficiently and increase economic returns (Susaeta et al., 2012). The bio-jet fuel produced from the oilseed crops could also help in reducing carbon emissions of the United States, as the country alone consumed 26.1% of the total jet fuel at the global level in 2017 (The Global Economy, 2019; US EIA, 2018) which contributed 4.81% of all the energy-related greenhouse gas emissions nationwide (US EIA, 2019).

Loblolly pine (*Pinus taeda* L.) is a fast-growing commercial tree species that covers 13.9 million ha in the southern United States (Oswalt et al., 2019; Schultz, 1997). Carinata (*Brassica carinata*) and white lupin (*Lupinus albus* L.) could be easily intercropped with loblolly pine, especially during the first eight to ten years of the plantation when the tree canopy has low shade effect on the intercropped feedstock. Carinata, also known as Ethiopian mustard, is an annual oilseed crop. It is frost and drought tolerant to a large degree, and due to the high percentage (40%) of erucic acid, it is unfit for human consumption but facilitates the higher rate of conversion to diesel and jet fuel. Carinata seed has a higher yield potential of 1870 l/ha compared to other cover crops (Seepaul et al., 2016) and could provide a net return of over $981/ha (Troy, 2017). In 2012, carinata was used as a 100% renewable jet fuel for the first time in a Canadian flight (Fougeres, 2012), which led to a 50% reduction in aerosol emission and black carbon (Hollis, 2015). White lupin is a non-native non-invasive annual legume that has 18.7% of crude protein content and 13% of oil content (Clark, 2014). It could supply up to 11.89 t dry biomass/ha/year when cultivated with cereal rye (*Secale cereale* L.) (Azo et al., 2012). As a leguminous crop, white lupin also provides the added benefit of soil enrichment and can fix about 157-196 kg/ha of N (Putnam, 1993). It can also be used as a forage crop, either grazed or harvested as baleage. The oil obtained from carinata and white lupin seeds could be processed using existing technologies for manufacturing bio-jet fuel to replace a portion of the total jet fuel consumed in the southern United States (US EIA, 2019).

Only a handful of studies have analyzed intercropping systems in the Southern United States. Susaeta et al. (2012) have assessed the economic feasibility of intercropping switchgrass (*Panicum virgatum*) in loblolly pine stands for emerging bioenergy markets. A few other studies have analyzed the impact of intercropping on productivity. Krapfl et al. (2017) and Shrestha et al. (2016) investigated the effect of intercropping switchgrass and loblolly pine on overall productivity. In contrast, Nambiar and Nethercott (1987) assessed the impact of leguminous crops on the growth of pine plantations. There exists a need for investigating the economic feasibility of intercropping oilseed crops and loblolly pine in the region for achieving the goals of ecological restoration, climate change mitigation, rural prosperity, and resilient local economies. In this regard, the objectives of this study are to compare the profitability of intercropping loblolly pine and oilseed crops relative to loblolly pine only and identify risks that affect the economic viability of intercropping oilseed crops with loblolly pine.

Table 1.1: The economics of bio-jet fuel production from different feedstocks. MJSP: Minimum Jet Fuel Selling Price.

Feedstock	**Study Area**	**Technology**	**MJSP/Cost**	**References**
Sugarcane	Brazil	First-generation sugars to bio-jet fuel via ethanol, and bagasse to bio-jet fuel via fast pyrolysis	US $ 1.38/l	Santos et al. (2018)
Sugarcane Algae	United States	Hydro-treating/Hydrocracking Based Conversion	US $ 0.73/l US $ 0.79/l	Agusdinata et al. (2011)
Corn Stover Switchgrass Short-rotation Woody biomass		Gasification and Fischer-Tropsch (FT) Synthesis	US $ 1.06/l US $ 4.42/l US $ 1.12/l	
Bagasse	United Kingdom	Direct sugar to hydrocarbons conversion pathway	US $ 2.78/l	Michailos (2017)
Palm oil Macauba oil Soybean oil Sugarcane Sugarcane+Eucalyptus	Brazil	Hydro-processed Esters and Fatty Acids (HEFA) Process FT Process	US $ 0.66/l US $ 0.55/l US $ 0.71/l US $ -0.22/l US $ 0.36/l	Klein et al. (2018)
Soybean	United States	HEFA process from renewable oils	US $ 0.90/l	Winchester et al. (2013)
Camelina Carinata Used Cooking Oil	Western Canada	Hydro-processed renewable jet fuel (with pre-treatment of oilseed feedstock)	US $ 0.69/l US $ 0.74/l US $ 0.74/l	Chu et al. (2017)
Camelina Carinata Jatropha	Australia	Hydro-de-oxygenation (HDO) process	US $ 0.55/l US $ 0.60/l US $ 0.82/l	Diniz et al. (2018)
Camelina	Canadian Prairies	HEFA process	US $ 1.06/l	Li et al. (2018)
Sugarcane	United States	The refining process for the conversion of lipids (from sugarcane) to jet fuel followed the Eco-fining process	US $ 1.40/l	Kumar et al. (2018)
Jatropha fruit	United States	Six-step pyrolysis based Bio-refinery process	US $ 1.43/l	Wang and Tao (2016)
Jatropha oil		Two-step bio-refinery process	US $ 1.52/l	

Methods

Selected Scenarios

We considered three cropping systems. In the first cropping system, only loblolly pine with no intercropping was considered. In the second cropping system, loblolly pine was rotated with carinata once every three years for the first eight (site index 15.3m), seven (site index 18.3m), and six (site index 21.3m) years. In the third cropping system, loblolly pine was rotated with carinata in the first year followed by two years of white lupin for the first eight (site index 15.3m), seven (site index 18.3m), and six (site index 21.3m) years (Table 1.2). Because of disease susceptibility, carinata needs to be planted once every three years (Seepaul et al., 2019). The growth of loblolly pine, carinata, and white lupin might get affected due to resource competition (Haile et al., 2016; Tian et al., 2017; Shrestha et al. 2016; Krapfl et al., 2017). Therefore, we considered several production scenarios within cropping systems for ascertaining the impact of potential changes in yields on the economics of intercropping systems (Table 1.3). The selected yield reductions were based on literature review and expert consultations.

Table 1.2: Cropping systems selected for the study. Site index (SI) is the average height of dominant trees in meters at the 25th year of the plantation. LP: Loblolly pine; C: Carinata; WL: White lupin.

	Cropping System LP+C			**Cropping System LP+C+WL**		
Stand Age	**SI 15.3m**	**SI 18.3m**	**SI 21.3m**	**SI 15.3m**	**SI 18.3m**	**SI 21.3m**
Year 1	Carinata	Carinata	Carinata	Carinata	Carinata	Carinata
Year 2	Fallow	Fallow	Fallow	White Lupin	White Lupin	White Lupin
Year 3	Fallow	Fallow	Fallow	White Lupin	White Lupin	White Lupin
Year 4	Carinata	Carinata	Carinata	Carinata	Carinata	Carinata
Year 5	Fallow	Fallow	Fallow	White Lupin	White Lupin	White Lupin
Year 6	Fallow	Fallow	Fallow	White Lupin	White Lupin	White Lupin
Year 7	Carinata	Carinata	-	Carinata	Carinata	-
Year 8	Fallow	-	-	White Lupin	-	-

Table 1.3: Production scenarios selected for the study. Numbers in the parenthesis represent the potential percentage yield reduction.

Scenarios	**Cropping system**
LP(0)	Loblolly Pine only with no intercropping (Baseline)
LP(0)+C(0)	Loblolly Pine + Carinata
LP(0)+C(0)+WL(0)	Loblolly Pine + Carinata + White Lupin
LP(-15)+C(-10)	Loblolly Pine (-15%) + Carinata (-10%)
LP(-15)+C(-10)+WL(-10)	Loblolly Pine (-15%) + Carinata (-10%) + White Lupin (-10%)
LP(-15)+C(-20)	Loblolly Pine (-15%) + Carinata (-20%)
LP(-15)+C(-20)+WL(-20)	Loblolly Pine (-15%) + Carinata (-20%) + White Lupin (-20%)
LP(-30)+C(-10)	Loblolly Pine (-30%) + Carinata (-10%)
LP(-30)+C(-10)+WL(-10)	Loblolly Pine (-30%) + Carinata (-10%) + White Lupin (-10%)
LP(-30)+C(-20)	Loblolly Pine (-30%) + Carinata (-20%)
LP(-30)+C(-20)+WL(-20)	Loblolly Pine (-30%) + Carinata (-20%) + White Lupin (-20%)

Crop Management

For simulating yield of a hectare of loblolly pine plantation located in the Lower Coastal Plain of South Georgia, seedlings of loblolly pine were planted in a grid of 2.5m×3m under LP(0) production scenario. The spacing between loblolly pine seedlings and the distance between rows of trees for intercropping was assumed to be 1.83m and 6.1m, respectively. For selected production scenarios, the planting density, fertilization application rate, and the time of application are reported in Table 1.4. While rotating loblolly pine with both carinata and white lupin until the canopy closure, mid-rotation fertilizer was not applied as white lupin fixes up to 196 kg/ha of N (Putnam, 1993). We have assumed that N fixed by white lupin will be available to loblolly pine seedlings.

Table 1.4: Planting density of loblolly pine and fertilizer application rate for selected cropping systems. LP: Loblolly pine, C: Carinata, and WL: White Lupin

Parameters			**Loblolly Pine Only**	**Intercropping Systems**	
				LP+C	**LP+C+WL**
Planting Density (seedlings/ha)			1333	897	
Fertilization (for Loblolly Pine)	N (kg/ha)	Year 02	112.1	112.1	112.1
		Thinning Year	224.2	224.2	-
	P (kg/ha)	Year 02	28	28	28
		Thinning Year	28	28	28
Fertilization (for Carinata)	N (kg/ha)	Over Crop Life	-	89.7	89.7

Source: Dickens et al. (2012) and Seepaul et al. (2016)

Carinata and white lupin were planted in a 3.7m strip between rows of loblolly pine seedlings, leaving a buffer of 1.22m at each side to minimize competition (Figure 1.1). Therefore, about 60% area of the total land area was used for carinata and white lupin production. Carinata was planted in a 0.4m spacing within that 3.7m row of loblolly pine plantation, and white lupin was planted in a 0.5m row spacing. The mean yield of carinata was 2311.02 kg/ha in South Georgia (Dr. Anderson, personal communication, April 3rd, 2020). Carinata was planted in mid-November with a planting density of 55 plants/m^2 and harvested in June. Total plant biomass yield (13.5 t/ha) of white lupin was adopted from the work of Azevedo et al. (2019). Based on expert consultations and field trials, the seed yield was assumed as 20% of total plant biomass, providing 2.7 t/ha of white lupin seeds.

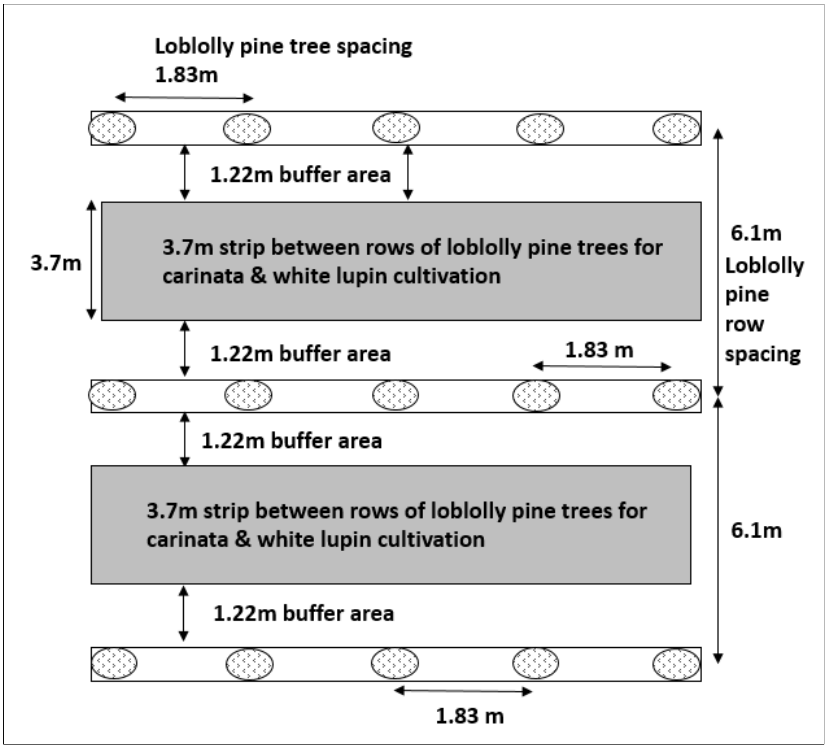

Figure 1.1: Intercropping layout plan for the study.

Economic Modeling

We used the Faustmann Model (Chang, 1998) for calculating the profitability of loblolly pine for every year over 30 years. We suitably extended the developed model to incorporate costs and incomes from carinata and white lupin. The profitability was calculated in terms of Land Expectation Value (LEV). The formula for LEV at any given time 't' is:

$$LEVt = \frac{NPVt \times (1+r)^t}{(1+r)^t - 1}$$

$$NPVt = \frac{P \times Q(t) - C(t)}{(1+r)^t}$$

where, P was the price of the commercial products obtained from loblolly pine, carinata, and white lupin, Q(t) was the quantities of the same products from each species at time t, C(t) was the cost associated with the development and management of a production system at time t, and r was the real discount rate (5%).

We used the growth and yield model developed by Gonzalez-Benecke et al. (2011) for estimating the volume of roundwood produced in an intensively managed loblolly pine stand located in the Lower Coastal Plain of South Georgia. Data were extracted for three selected site indices. For loblolly pine with no intercropping, the thinning was undertaken at ages 17, 15, and 13 years for site indices 15.3m, 18.3m, and 21.3m, respectively, before clear-cutting the plantation at the stand age at which the LEV maximizes. When loblolly pine rotated with carinata only and both carinata and white lupin, thinning was undertaken at the age of 17, 16, and 14 years for site indices 15m, 18.3m, and 21.3m, respectively, before clear-cutting the plantation at the stand age at which the LEV maximizes.

Table 1.5: Cost estimation for the establishment and development of loblolly pine stand.

Items	**Cost (US $/ha)**
Mechanical Site Preparation	518.9
Chemical Site Preparation	185.3
Planting Cost	
Loblolly pine only	252.2
Loblolly pine with intercropping	169.5
Total Establishment Cost	
Loblolly pine only	956.5
Loblolly pine with intercropping	873.8
Herbaceous Weed Control	38.2
Mid-rotation Hardwood Control	163.1
Fertilization at Year 02	215
Fertilization at the Thinning Age	407.7
Annual Property Tax	14.8
Annual fire Protection	4.9
Annual Stand Management	4.9

The prices of roundwood products were obtained from the Timber Mart-South located at the University of Georgia's Warnell School of Forestry and Natural Resources. The average prices of pine sawtimber, chip-n-saw, and pulpwood were \$24.91/t, \$18.29/t, and \$11.91/t, respectively, in the third quarter of 2017. The costs associated with site preparation, establishment, and management of loblolly pine stands were obtained from Dickens et al. (2014) and Dooley and Barlow (2013) (Table 1.5).

Costs associated with land preparation, crop maintenance, and harvesting operation for carinata production (Table 1.6) were obtained from the National Peanut Research Laboratory, and the price of carinata seeds was \$400/t during 2017-2018 (National Peanut Research Laboratory, 2018). The economic analysis was performed on the assumption that the yield remained constant for each year for both carinata and white lupin. Costs associated with the production and maintenance of white lupin are reported in Table 1.7. The average price of white lupin seeds was \$185/t (Clark, 2014).

Table 1.6: Estimated production cost for carinata.

Cost Components	**Cost (US \$/ha)**
Establishment	
Land Preparation	43.2
Seed	61.8
Crop Maintenance	
Fertilizer	296.4
Crop Protection	61.8
Fuel and Harvesting	
Pre-harvest	13.6
Harvest	111.2
Delivery	12.4
Insurance	49.4
Interest on Operating Capital (6%)	39
Total Cost	688.7

Table 1.7: Estimated cost for white lupin production

Cost Components	Cost (US $/ha)	Source
Seed	395.2	Dr. Anderson, Per. Comm., April 20, 2019
Fertilizer (P & K) and Pre-Herbicide	98.8	Dr. Anderson, Per. Comm., April 20, 2019
Repairs and Maintenance	16.4	
Fuel and Lubrication	27.4	Putnam (1993)
Interest on Operating Capital (6%)	32.3	
Total Cost	570.1	

Sensitivity and Risk Analyses

Using @Risk 7.6 software (www.palisade.com), which uses the Monte Carlo Simulation procedure for undertaking sensitivity and risk analyses, we first determined the sensitivity of LEVs of selected production systems to various input variables. The input variables chosen for the sensitivity analysis were interest rate, cost of site preparation and planting for loblolly pine, cost of initial fertilization for loblolly pine, the price of carinata and white lupin seeds, and the seed yields of carinata and white lupin (Table 1.8). Triangular probability distribution was used for all the input variables. The triangular distribution is defined by minimum, maximum, and the most likely values and is more useful when the distribution of the variables is unknown. The input variables were varied by ±20% in the triangular distribution. We used a similar set up for undertaking risk analysis for determining the probability of loss associated with a production system involving intercropping relative to a production system where only loblolly pine is planted for a similar site index. We simulated the developed model for 5000 iterations for undertaking sensitivity and risk analyses.

Table 1.8: Variables and their ranges selected for undertaking risk and sensitivity analyses

Triangular Distribution	Minimum	Most Likely	Maximum
Interest Rates	4%	5%	6%
Site Preparation Cost & Planting Loblolly Pine	\$699/ha	\$873.8/ha	\$1048.5/ha
Cost of Initial Fertilization for loblolly pine	\$172/ha	\$215/ha	\$258/ha
Price of Carinata Seeds	\$320/t	\$400/t	\$480/t
Seed Yield of White Lupin	2.16 t/ha	2.7 t/ha	3.24 t/ha
Price of White Lupin Seeds	\$148/t	\$185/t	\$222/t
Yield of Carinata Seeds	1848.8 kg/ha	2311.02 kg/ha	2773.2 kg/ha

Results and Discussions

Profitability Assessment

For site index 15.3m, the LEV of LP(0) production scenario was \$762/ha at a 24-years rotation period. The profitability of the LP(0)+C(0) production scenario increased to \$1709/ha, though the optimal rotation age remained the same as the LP(0) production scenario. Moreover, LP(0)+C(0)+WL(0) production scenario yielded a higher LEV of \$1904/ha compared to both the LEV of the LP(0) production scenario and LP(0)+C(0) production scenario. On the other hand, the optimal rotation age was a year shorter than both LP(0) production scenario and LP(0)+C(0) production scenario (Figure 1.2). For the site index 18.3m, the LEV of LP(0)+C(0) production scenario was \$2729/ha, which was approximately 1.4 times higher compared to the LEV of the LP(0) production scenario. The LEV of LP(0)+C(0)+WL(0) production scenario increased by \$225/ha compared to LP(0)+C(0) production scenario. The optimal rotation age was a year shorter for both LP(0)+C(0) and LP(0)+C(0)+WL(0) production scenarios compared to LP(0) production scenario. For the site index 21.3m, the LEV of the LP(0) production scenario was \$3188/ha at a 21-years rotation period. Production scenarios LP(0)+C(0) and LP(0)+C(0)+WL(0) yielded LEVs of \$3674/ha and \$3935/ha at a 21-years rotation period, respectively. The optimal rotation age remained the same for both LP(0)+C(0) and LP(0)+C(0)+WL(0) production scenarios relative to the LP(0) production scenario (Figure 1.2). Results indicate that intercropping could yield higher profits to southern forest landowners in the absence of yield changes. Our results are similar to the results of Susaeta et al. (2012), where the intercropping loblolly pine with switchgrass increased the profitability of forest landowners.

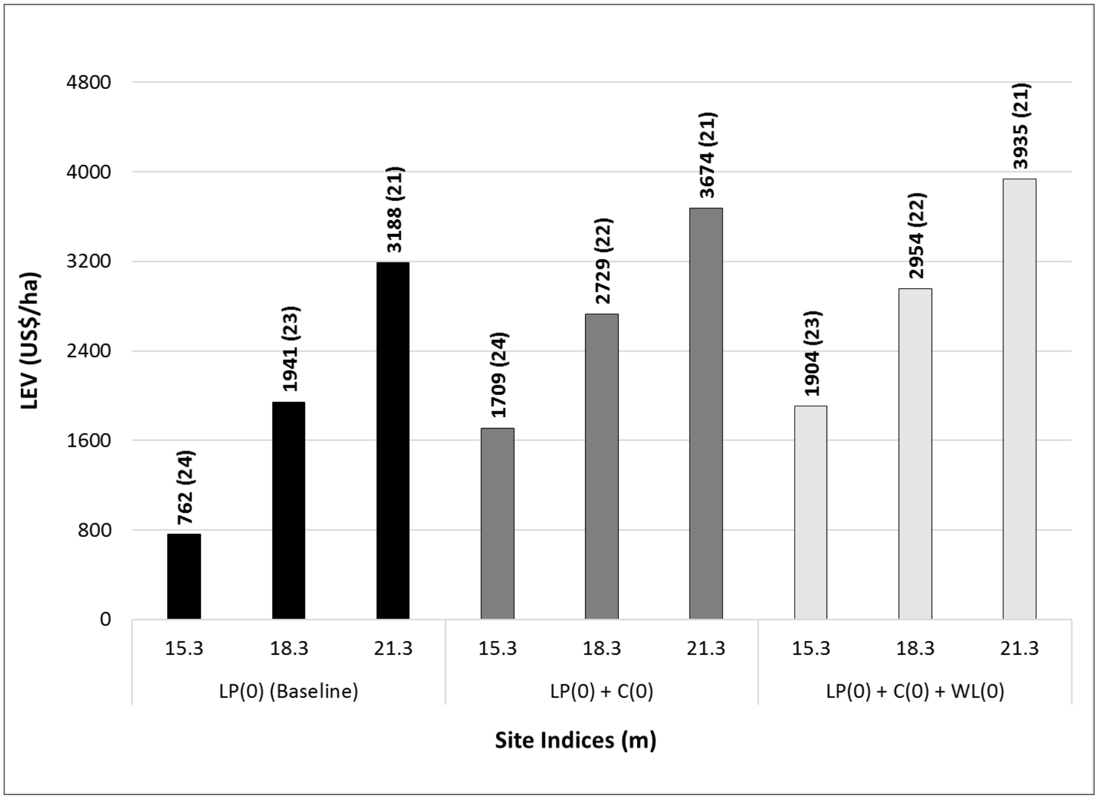

Figure 1.2: Land Expectation Values (LEVs) when there is no loss in yields. Number in the parenthesis is optimal rotation age in years.

In the LP(-15)+C(-10) production scenario, the LEVs of site indices 15.3m and 18.3m remained higher compared to the baseline LP(0) production scenario (Figure 1.3). The optimal rotation age was a year longer for site index 15.3m, whereas optimal rotation age remained the same for site 18.3m compared to the LP(0) production scenario. However, the LEV of site index 21.3m decreased by $415/ha though the optimal rotation age remained the same compared to the

LP(0) production system. For LP(-15)+C(-20) production scenario, the LEV of site index 15.3m was $80/ha higher, and the optimal rotation age was a year longer than LP(0) production scenario. The LEVs of site indices 18.3m and 21.3m were $220/ha and $585/ha lower than the baseline LP(0) production scenario, respectively. However, the optimal rotation ages did not change for site indices 18.3m and 21.3m relative to LP(0) production scenario (Figure 1.3).

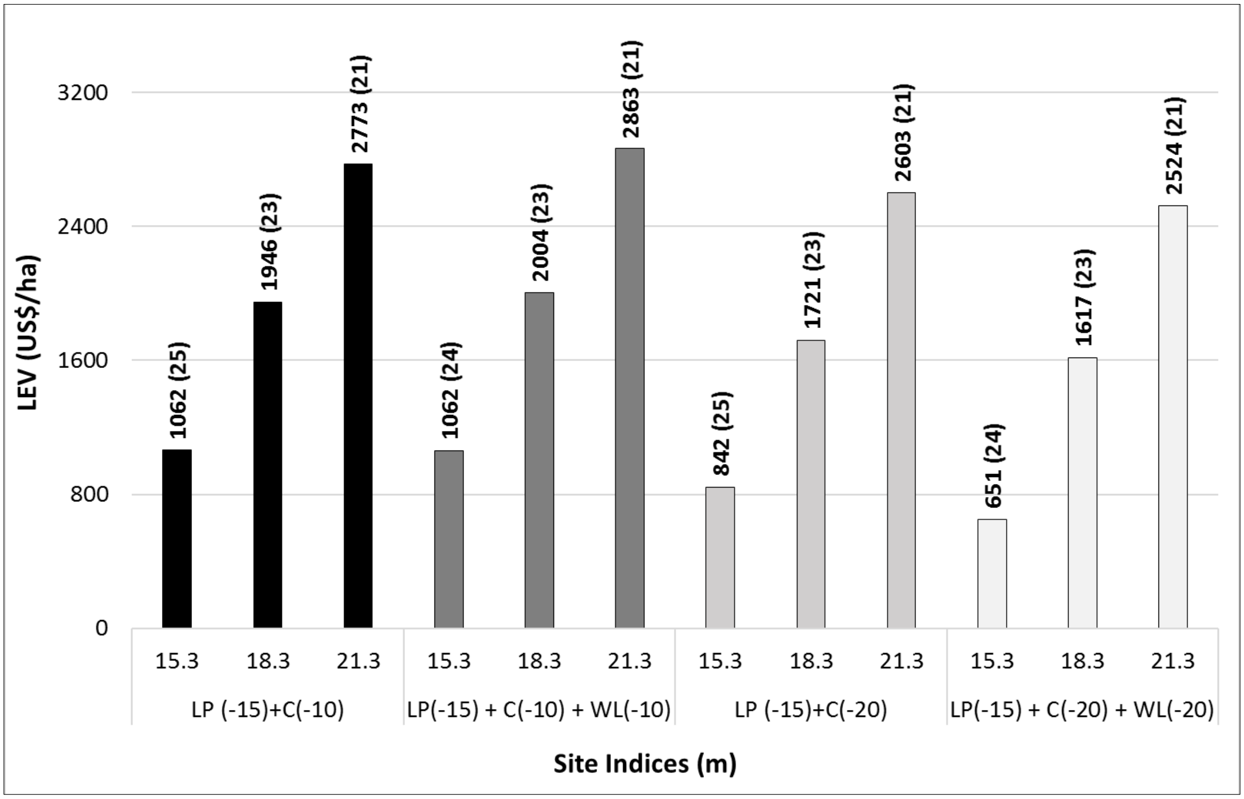

Figure 1.3: Land Expectation Values (LEVs) when loblolly pine growth reduced by 15% and carinata and white lupin by 10% and 20%, respectively. Number in the parenthesis is optimal rotation age in years.

In the LP(-15)+C(-10)+WL(-10) production scenario, intercropping remained profitable compared to the LP(0) production scenario across site indices 15.3m and 18.3m. The optimal rotation ages remained the same for site indices 15.3m and 18.3m than the LP(0) production scenario for the same site indices. The LEV of site index 21.3m decreased by $325/ha, and the optimal rotation age remained the same compared to the baseline. For LP(-15)+C(-20)+WL(-20) production scenario, the profitability was lower than the LP(0) production scenario for all the site indices. The LEVs were reduced by $111/ha, $325/ha, and $664/ha for the site indices 15.3m, 18.3m, and 21.3m, respectively, compared to the LP(0) production scenario for the same site indices. However, no changes in optimal rotation ages were noticed for all the site indices compared to the baseline production scenario (Figure 1.3).

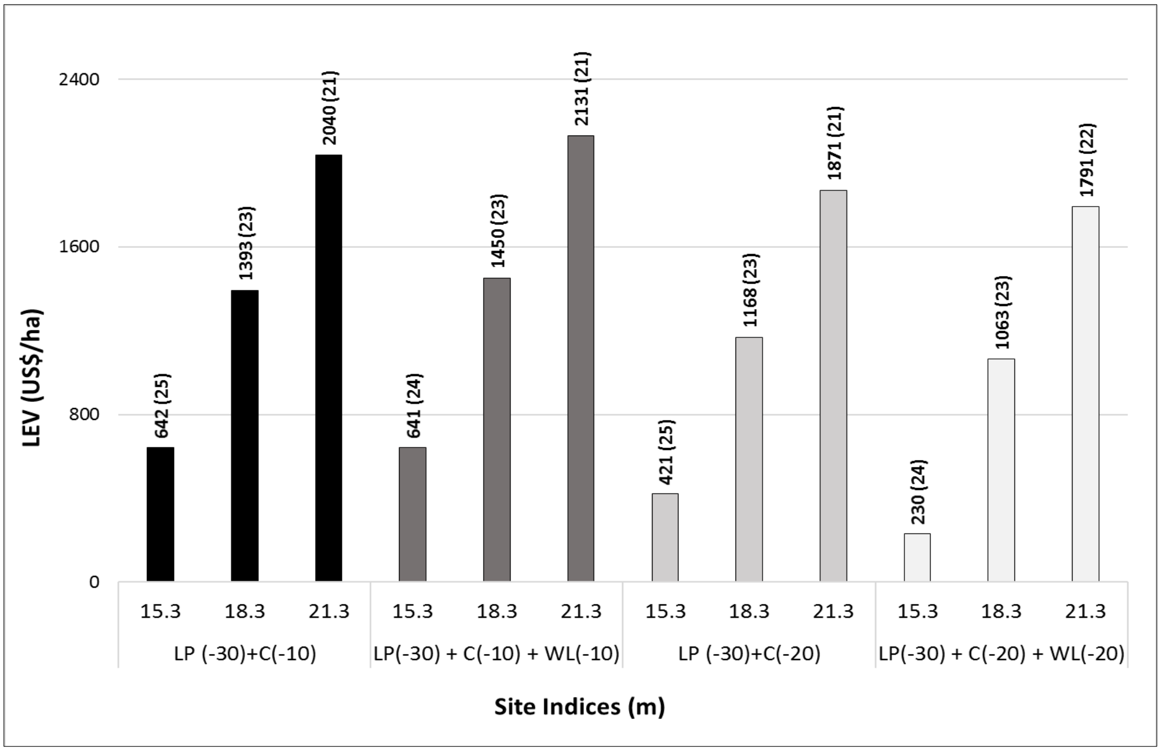

Figure 1.4: Land Expectation Values (LEVs) when loblolly pine growth reduced by 30% and carinata and white lupin by 10% and 20%, respectively. Number in the parenthesis is optimal rotation age in years.

For LP(-30)+C(-10) production scenario, the LEVs were lower relative to the LP(0) production scenario for all the three site indices. The optimal rotation was a year longer for site index 15.3m and remained the same for site indices 18.3m and 21.3m compared to the LP(0) production scenario for the same site indices. In LP(-30)+C(-10)+WL(-10) production scenario, the LEVs were $121/ha, $491/ha, and $1057/ha lower than the baseline LP(0) production scenarios for site indices 15.3m, 18.3m, and 21.3m, respectively. However, The optimal rotation ages were the same as the baseline for all the site indices. In LP(-30)+C(-20) production scenario, the LEVs of intercropping went down by $340/ha, $774/ha, and $1317/ha compared to LP(0) production system for site indices 15.3m, 18.3m, and 21.3m, respectively. The optimal rotation age was a year longer for site index 15.3m relative to the baseline LP(0) production scenario but remained the same as the baseline for site indices 18.3m and 21.3m. In LP(-30)+C(-20)+WL(-20) production scenario, the profitability reduced by $531/ha, $878/ha, and $1396/ha for site indices 15.3m, 18.3m, and 21.3m, respectively, compared to LP(0) production scenario. Moreover, no changes in optimal rotation ages were noticed for site indices 15.3m and 18.3m compared to the baseline production scenario. The optimal rotation age was a year longer for site index 21.3 relative to LP(0) production scenario (Figure 1.4).

Sensitivity Analysis

For LP(0) production system, the real interest rate had the most significant impact on the LEV, suggesting that a unit increase in the real interest rate would at least decrease the LEV by 0.95 standard deviations on average (Table 1.9). The cost of site preparation and planting was the second most significant variable and negatively associated, as well. For the other production systems which involved intercropping, the interest rate was the most significant variable and negatively related to the LEV. The yield potential of carinata seeds and the price of carinata seeds had the second most significant impact and were positively associated with the LEV. In those production scenarios where loblolly pine was rotated with both carinata and white lupin, the yield and price of white lupin seeds were the fourth and fifth most influential variables and were positively associated with LEVs. The cost of site preparation and planting and initial fertilization had comparatively lower impacts on the LEVs of intercropping production scenarios.

Table 1.9: Standardized regression coefficients showing the impact of selected input variables on the land expectation values.

Scenarios	**Site Index**	**Interest Rate**	**Site Prep. & Planting**	**Loblolly Pine Fertilization**	**Carinata Seed**		**Lupin Seed**	
					Yield	**Price**	**Yield**	**Price**
LP(0)	15.3	-0.93	-0.35	-0.07	-	-	-	-
LP(0)	18.3	-0.96	-0.26	-0.05	-	-	-	-
LP(0)	21.3	-0.97	-0.2	-0.04	-	-	-	-
LP(0)+C(0)	15.3	-0.78	-0.24	-0.05	0.41	0.41	-	-
LP(0)+C(0)	18.3	-0.85	-0.2	-0.04	0.34	0.34	-	-
LP(0)+C(0)	21.3	-0.93	-0.18	-0.04	0.22	0.22	-	-
LP(0)+C(0)+WL(0)	15.3	-0.72	-0.2	-0.05	0.36	0.36	0.31	0.31
LP(0)+C(0)+WL(0)	18.3	-0.81	-0.18	-0.04	0.31	0.31	0.22	0.22
LP(0)+C(0)+WL(0)	21.3	-0.89	-0.16	-0.04	0.2	0.2	0.2	0.2
LP(-15)+C(-10)	15.3	-0.73	-0.27	-0.06	0.43	0.43	-	-
LP(-15)+C(-10)	18.3	-0.82	-0.23	-0.05	0.35	0.36	-	-
LP(-15)+C(-10)	21.3	-0.92	-0.21	-0.05	0.24	0.24	-	-
LP(-15)+C(-10)+WL(-10)	15.3	-0.67	-0.24	-0.05	0.38	0.38	0.33	0.32
LP(-15)+C(-10)+WL(-10)	18.3	-0.79	-0.21	-0.05	0.33	0.33	0.24	0.24
LP(-15)+C(-10)+WL(-10)	21.3	-0.86	-0.19	-0.04	0.21	0.22	0.21	0.21
LP(-15)+C(-20)	15.3	-0.75	-0.3	-0.07	0.41	0.41	-	-
LP(-15)+C(-20)	18.3	-0.83	-0.24	-0.05	0.33	0.33	-	-
LP(-15)+C(-20)	21.3	-0.93	-0.22	-0.05	0.21	0.22	-	-
LP(-15)+C(-20)+WL(-20)	15.3	-0.67	-0.26	-0.06	0.36	0.36	0.31	0.31
LP(-15)+C(-20)+WL(-20)	18.3	-0.79	-0.22	-0.05	0.31	0.31	0.22	0.22
LP(-15)+C(-20)+WL(-20)	21.3	-0.89	-0.2	-0.04	0.2	0.2	0.2	0.2
LP(-30)+C(-10)	15.3	-0.65	-0.31	-0.07	0.48	0.49	-	-
LP(-30)+C(-10)	18.3	-0.77	-0.26	-0.06	0.41	0.41	-	-
LP(-30)+C(-10)	21.3	-0.87	-0.25	-0.06	0.28	0.28	-	-
LP(-30)+C(-10)+WL(-10)	15.3	-0.58	-0.26	-0.06	0.41	0.41	0.35	0.35
LP(-30)+C(-10)+WL(-10)	18.3	-0.73	-0.24	-0.05	0.37	0.38	0.27	0.27
LP(-30)+C(-10)+WL(-10)	21.3	-0.83	-0.22	-0.05	0.25	0.26	0.25	0.25
LP(-30)+C(-20)	15.3	-0.66	-0.33	-0.07	0.46	0.46	-	-
LP(-30)+C(-20)	18.3	-0.78	-0.28	-0.06	0.39	0.38	-	-
LP(-30)+C(-20)	21.3	-0.89	-0.26	-0.06	0.25	0.25	-	-
LP(-30)+C(-20)+WL(-20)	15.3	-0.58	-0.29	-0.07	0.4	0.4	0.35	0.34
LP(-30)+C(-20)+WL(-20)	18.3	-0.75	-0.26	-0.06	0.36	0.36	0.26	0.26
LP(-30)+C(-20)+WL(-20)	21.3	-0.83	-0.23	-0.05	0.23	0.24	0.23	0.23

Risk Analysis

Considering the LEV of LP(0) production scenario as a threshold value, i.e., \$762/ha, \$1941/ha, and \$3188/ha for site indices 15.3m, 18.3m, and 21.3m, respectively, Figure 1.5 shows the percentage by which the profitability of intercropping system falls below the corresponding threshold LEV value. Therefore, if forest landowners want to switch to intercropping instead of managing their lands only for loblolly pine without intercropping, Figure 1.5 illustrates the probability of loss associated with the decision.

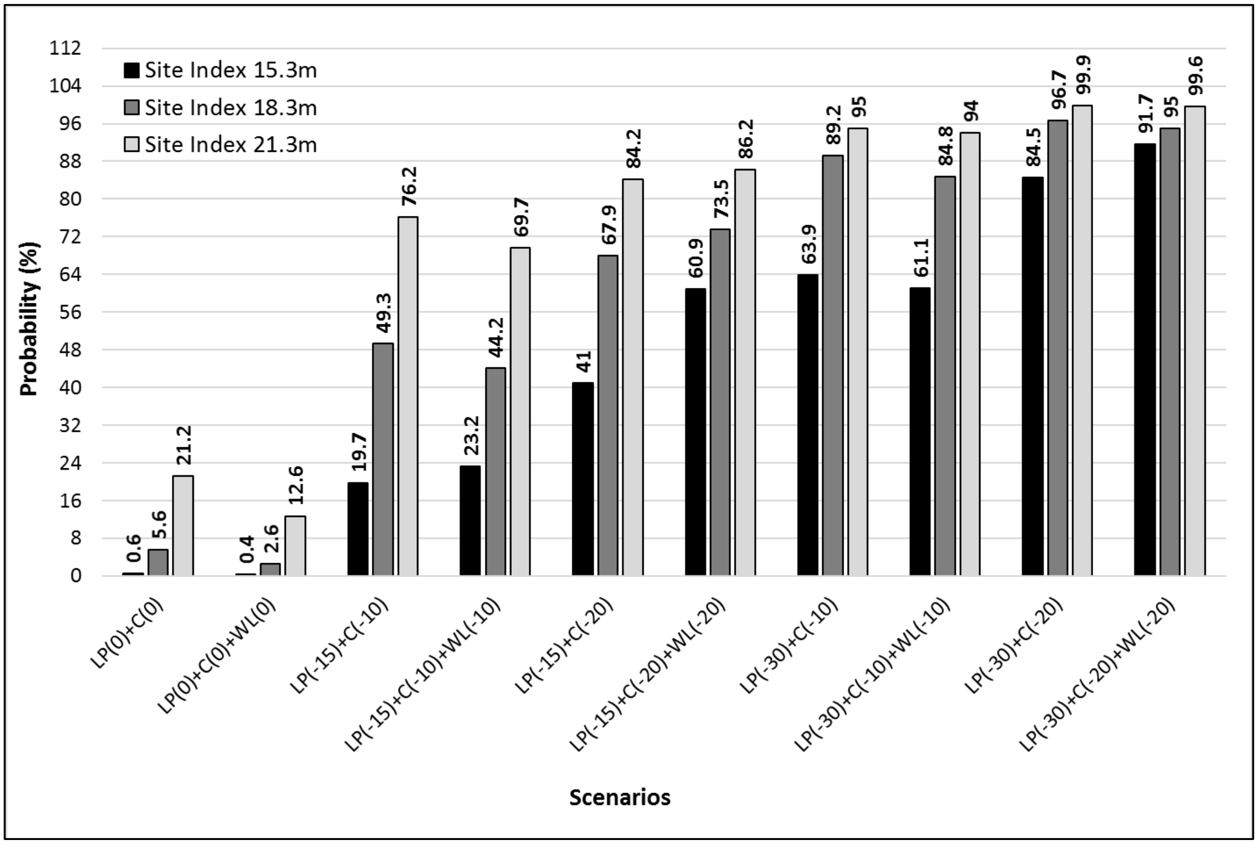

Figure 1.5: The probability of obtaining a Land Expectation Value (LEV) of intercropping which is less than the LEV of managing the forestland for loblolly pine with no intercropping

In LP(0)+C(0)+WL(0) production scenario, the probabilities that the LEVs would be lower than the LEVs of LP(0) production scenario were 0.4%, 2.6%, and 12.6% for site indices 15.3m, 18.3m, and 21.3m, respectively. The percentage increased to 0.6%, 5.6%, and 21.2% for site indices 15.3m, 18.3m, and 21.3m, respectively for LP(0)+C(0) production scenario. However, the percentage increased gradually for production scenarios with greater yield losses across selected species. In LP(-15)+C(-20)+WL(-20) production system, the probabilities that the LEVs would be less than the LEVs of LP(0) production scenario were 60.9%, 73.5%, and 86.2% for site indices 15.3m, 18.3m, and 21.3m, respectively. The percentage increased to 91.7%, 95%, and 99.6% for site indices 15.3m, 18.3m, and 21.3m, respectively for LP(-30)+C(-20)+WL(-20) production scenario. Higher risks were associated with the production systems with greater yield losses (Figure 1.5).

Conclusion

We analyzed the economic viability of intercropping loblolly pine with white lupin and carinata oil-seed crops in this study, by comparing the profitability of loblolly pine only production system to the various intercropping production systems. Results from the economic model indicate that intercropping would be a profitable alternative for a southern forest landowner for managing their forestland resources, unless the yields of loblolly pine, carinata, and white lupin are significantly reduced due to competition for nutrients, variability in water availability, shade effects, etc. The LEVs of production systems were sensitive to the interest rate and prices and yield of carinata seeds. Risk analysis informed that the percentage of obtaining an LEV lower than the LEV of loblolly pine production system increases with projected yield losses.

A need exists to conduct long term field trials for understanding the effects of intercropping on yields of carinata, white lupin, and loblolly pine. A need also exists to conduct studies on understanding the perceptions of forest landowners about the intercropping for devising suitable extension and outreach strategies, which can help in increasing the adoption of intercropping production systems in the region. We hope that this study will feed into future research, which takes an integrated approach for promoting bio-economy development in the southern United States.

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CHAPTER 2

ASSESSING CARBON BENEFITS OF INTERCROPPING LOBLOLLY PINE AND CARINATA FOR BIO-JET FUEL PRODUCTION IN THE SOUTHERN UNITED STATES[2]

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[2] Akter, H.A. & Dwivedi, P. To be submit to the *Journal of Industrial Ecology*.

Abstract

The commercial aviation industry is currently responsible for 2% of the total human-induced carbon dioxide emissions worldwide. Jet fuel derived from agricultural feedstocks could reduce carbon emissions from the aviation sector. This study determines carbon savings related to intercropping loblolly pine (*Pinus taeda* L.) with carinata (*Brassica carinata*) and compared the same with carbon savings associated with loblolly pine only. We adopted an integrated life cycle analysis approach to quantify the overall carbon savings from the utilization of wood products and avoided carbon emissions from the substitution of conventional jet fuel with carinata-based bio-jet fuel. The functional unit for analysis was a hectare of intensively managed loblolly pine plantation in the Southern United States. The system boundary included all the steps starting from forest management with carinata, the use of wood products, the decay of wood products in landfills, and the substitution of conventional jet fuel with bio-jet fuel. Carbon stored in wood products was 5.46 t, 6.75 t, and 11.52 t C/ha higher than carbon stored in landfill at the end of the planning period (100 years) for the intercropping system for site indices 15.3m, 18.3m, and 21.3m, respectively. The total avoided carbon savings from carinata-based bio-jet fuel was 0.66 t, 1.29 t, and 2.15 t C/ha for site indices 21.3m, 18.3m, and 15.3m, respectively at the end of the planning period. Devoting the forestland for intercropping to produce bio-jet fuel decreased the total carbon storage by 4.71 t, 6.51 t, and 14.24 t C/ha than loblolly pine only management scenario for site indices 15.3, 18.3m, and 21.3m, respectively. Our results indicate that intercropping could reduce the total aboveground carbon savings relative to loblolly pine only production system over time, and thereby more research is needed before promoting intercropping of oilseed crops in the Southern United States.

Introduction

The total number of air passengers reached 4.5 billion in 2019 (ATAG, 2020), and it is likely that 8.2 billion passengers will opt for air travel by 2037 (IATA, 2018). Currently, the global jet fuel demand is 8% of the total refined petroleum product demand of 1.18 billion liters per day; however, it is likely to increase to about 10% by the end of 2040 (Vertz and Sayal, 2018). The consumption of petroleum-based jet fuel generated 915 Mt of carbon dioxide emissions worldwide in 2019 (ATAG, 2020). The commercial aviation industry is currently responsible for 2% of the total anthropogenic carbon dioxide emissions (ATAG, 2020), and this percentage is expected to increase to 15% by 2050 (Michailos, 2017) in the absence of any initiatives.

The International Air Transport Association set three goals to reduce the carbon footprint of the aviation sector through the adoption of Carbon Offsetting and Reduction Scheme for International Aviation. The first goal is to improve the average annual fuel efficiency by up to 1.5% by 2020. The second goal is to reduce carbon emissions to 50% by 2050 compared to the reference year 2005. The third goal is to stabilize carbon emissions at the 2020 level to achieve carbon-neutral growth (IATA, 2018). For attaining the carbon-neutral growth of the aviation industry, around 1,039 Mt of carbon dioxide emissions need to be mitigated by the end of 2050 (ICAO, 2016).

Jet fuel derived from biomass is a promising solution for reducing carbon dioxide emissions of the aviation sector. Several studies have analyzed carbon benefits related to the use of biomass-based jet fuels across feedstocks (Table 2.1), suggesting that the use of bio-jet fuel saves between 29% and 80% of carbon dioxide emissions depending on the type of feedstock and jet fuel production pathway. The majority of existing studies have simultaneously analyzed the carbon emissions reduction potential and economics of bio-jet fuel from agricultural feedstocks.

Table 2.1: Greenhouse gas emissions of bio-jet fuel production from different feedstocks.

Feedstock	**Study Area**	**Technology used**	**GHG Emissions (gCO$_2$eq MJ^{-1})**	**Emission reduction (%)**	**Reference**
Sugarcane	Brazil	Frist generation sugars to bio-jet fuel via ethanol, and bagasse to bio-jet fuel via fast pyrolysis	<42.5		(Santos et al., 2018)
Alcohol-to-jet (ATJ) fuel	Global Review	Three-step ATJ process: alcohol dehydration, oligomerization, and hydrogenation	40		(Wang and Tao, 2016)
Oil-to-jet (OTJ) fuel		Hydro-processed renewable (HRJ) jet fuel pathway	40		
Gas-to-jet (GTJ) fuel		Catalytic hydro-thermolysis to jet fuel	18		
Sugar-to-jet fuel		Pyrolysis-to-jet fuel process	15		
Jatropha	Brazil	Synthetic paraffinic kerosene (SPK) production from *Jatropha curcas*	40	55	(Bailis and Baka, 2010)
Poplar Biomass	United States	Acetogen fermentation process followed by dilute acid pretreatment and enzymatic hydrolysis. Poplar biomass is fermented to acetic acid and then hydro-processed, and oligomerized to jet fuel.	60-66	29-35	(Budsberg et al., 2016)
Microalgae	United States	Hydrothermal liquefaction (HTL) pathway	35.2	55.4%	(Fortier et al., 2014)
Camelina	United Kingdom	Bio-Synthetic Paraffinic Kerosene (Bio-SPKs) through hydro-processed renewable jet fuel production pathway	31.4	70	(Lokesh et al., 2015)
Microalgae			40.1	58	
Jatropha			38	64	
Used Cooking Oil (UCO)	United States	Hydro-processed Esters and Fatty Acids (HEFA)	28	68	(Jong et al., 2017)
Jatropha			55		
Camelina			47		
Willow		Fischer–Tropsch (FT)	9		
Poplar		(GHG emission savings:	10		
Corn Stover		86–104%)	13		
Forestry residues			6		
Forestry residues		Hydrothermal Liquefaction (HTL)	18	77-80	
Forestry residues		Pyrolysis	22	54-75	
Corn		Alcohol-to-Jet (ATJ)	54		
Corn stover			35	60-75	
Sugarcane			31	71-75	
Sugarcane		Direct Sugars to Hydrocarbons (DSHC)	76		
Open Pond-Based Micro-Algae	China	Algae oil extraction through lipid fractionation process and refinery based Bio-SPK production using extracted oil as an input	159		(Ou et al., 2013)

Sufficient land resources, coupled with innovative farming practices, are needed for ensuring the production of biomass-based jet fuel in the United States. Intercropping is the process of planting crops in between rows of trees (Kemp, 2011), which could be adopted to cultivate feedstocks for bio-jet fuel production. The forestlands cover 309.78 million ha of land in the United States (Oswalt et al., 2019), and offset about 16% of the total carbon dioxide emissions per year nationwide (Durkay and Schultz, 2016). Udawatta and Jose (2012) found that carbon sequestration potential of agroforestry systems in the United States could be 53×10^7 t C/year, which would offset about 33% of carbon dioxide emissions nationwide. Sharrow and Ismail (2004) conducted an agroforestry study in Oregon, incorporating Douglas-fir (*Pseudotsuga menziesii*) with perennial ryegrass (*Lolium perenne*) and subclover (*Trifolium subterraneum*) and found that agroforestry system could store 740 kg/ha/year more carbon than traditional forest. These studies clearly indicate that intercropping could provide an alternative path to manage forestland resources for simultaneously producing forest products and biomass for bio-jet fuel production.

Loblolly pine (*Pinus taeda* L.) is a fast-growing softwood species covering 13.9 million ha of land in the Southern United States (Oswalt et al., 2019; Schultz, 1997). Intercropping carinata (*Brassica carinata*) with reforested loblolly pine stands for the initial few years could provide us necessary oil, which could be further refined for bio-jet fuel production to reduce the carbon footprint of the commercial aviation sector. Carinata is an annual oilseed crop known as Ethiopian mustard. It is frost and drought tolerant and prevents soil erosion and nutrient losses to water bodies, making it superior compared to other crops. The oil obtained from carinata has a high amount of erucic and linoleic acid, which makes it desirable to process using existing technologies for manufacturing bio-jet fuel (Seepaul et al., 2019). Carinata has a high potential to grow in the Southern United States because of the topography and climatic condition. About 45.6% of agricultural land in Georgia, 3.04% of land in Alabama, and 0.81% of land in Florida are suitable for carinata production and together could produce between 1.87 and 3.91 Mt of carinata leading to a total production of between 980 and 2045 millions liters of bio-jet fuel (Alam and Dwivedi, 2019). The southern states alone consumed about 12.1% of the overall jet fuel consumed at the national level in 2017 (US EIA, 2019). Therefore, bio-jet fuel produced from carinata could replace some portion of the total jet fuel consumption in the Southern United States, and thereby reducing total carbon dioxide emissions at the national level from the aviation sector.

Existing studies focusing on the role of forests and wood products in storing carbon suggest that softwood products used in single-family housing can save around 4.4 Mt of carbon dioxide emissions annually (Meil et al., 2007). Perez-Garcia et al. (2005) suggested that short harvesting cycles significantly reduced atmospheric carbon when carbon pool from the forest, forest products, and displacement of conventional products by forest products were considered. Dwivedi et al. (2014) concluded that the amount of carbon sequestration in wood products and wood present in landfills decreased up to 1.6 t/ha when pulpwood was used for bioenergy development instead of paper manufacturing. Intensive management of forestland can sequester more carbon than non-intensive management, and the difference of carbon sequestration between the two ranged between 38.6 to 0.03 t C/ha for age 27 and 10 years, respectively (Dwivedi et al., 2016).

Existing studies focus on carbon saving from wood-based product and energy usage and how different management strategies affect total carbon sequestration in the forestland over time. However, there are only a handful of studies that have analyzed intercropping systems in the Southern United States. Susaeta et al. (2012) assessed the economic feasibility of intercropping switchgrass (*Panicum virgatum*) and loblolly pine for emerging bioenergy markets and found that intercropping would be profitable if switchgrass prices were ≥ \$30/t provided that the competition between the species was minimal. Krapfl et al. (2017) analyzed the impact of intercropping switchgrass and loblolly pine on the overall productivity and found that interspecific competition reduced average height, diameter, and volume of loblolly pine seedlings. Shrestha et al. (2016) analyzed the ecosystem carbon balance of intercropping loblolly pine and switchgrass and reported that shading from loblolly pine and decreased root proliferation reduced switchgrass root productivity.

There exists a need for investigating the environmental feasibility of intercropping loblolly pine and carinata oilseed crop in the Southern United States for defining the role of innovative intercropping systems in reducing carbon emissions. In this regard, the objective of this study is to compare the carbon savings achieved from intercropping loblolly pine and carinata for joint production of roundwood products and bio-jet fuel versus loblolly pine only management system in the Southern United States.

Methods

Life Cycle Analysis

A life cycle analysis was performed to determine total carbon savings and quantify greenhouse gas (GHG) emissions for producing timber from loblolly pine plantation for wood products. A similar life cycle approach was also adopted to calculate the total GHG emissions for intercropping loblolly pine and carinata to produce both roundwood products and carinata seeds for bio-jet fuel. The functional unit for this analysis was a hectare of intensively managed loblolly pine plantation in South Georgia. The life cycle analysis was performed for a 100-years simulation period, and the rotation age of loblolly pine was based on the results from economic models in

Chapter 01 of this thesis. Figure 2.1 shows the selected system boundary for producing roundwood products and bio-jet fuel from an intensively managed loblolly pine plantation.

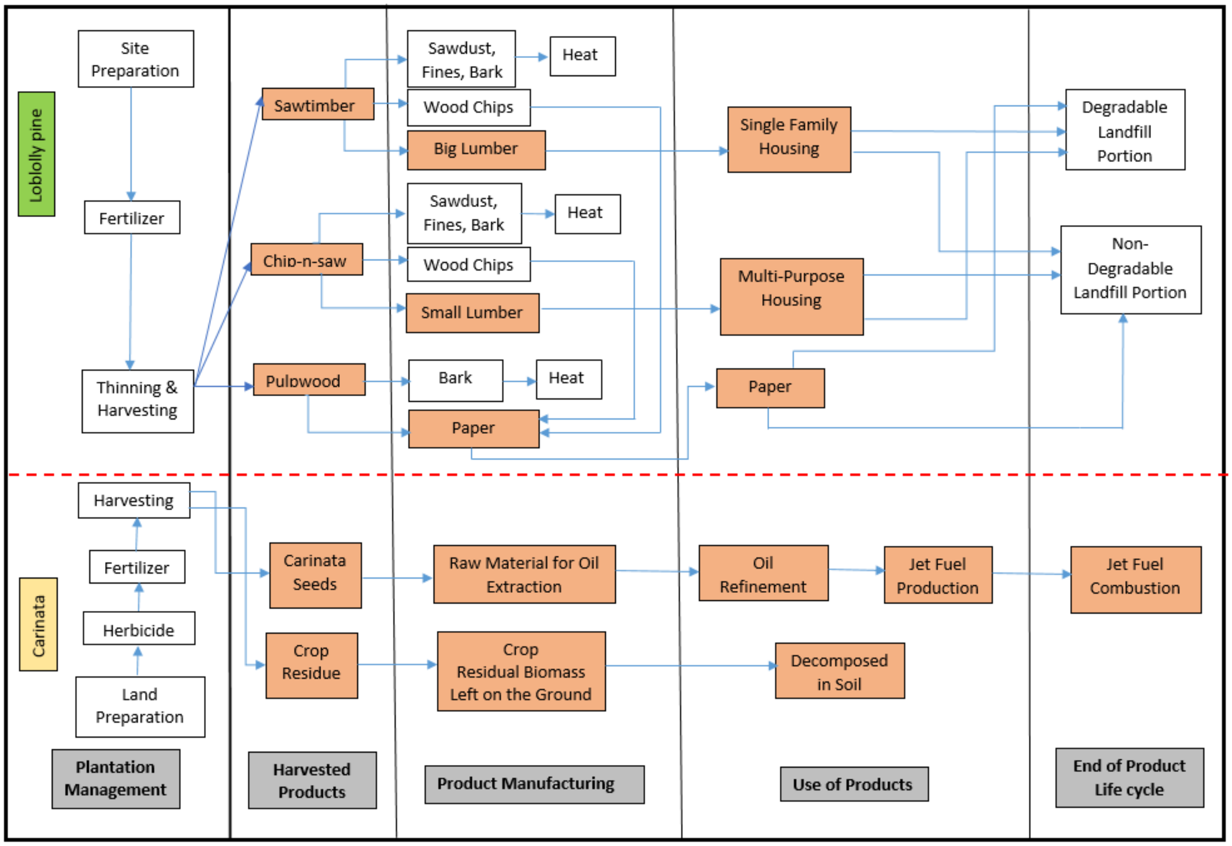

Figure 2.1: System boundary for loblolly pine only management and intercropping with carinata oilseed crops production system.

The system boundary for loblolly pine only management included the following stages: production of roundwood (sawtimber, chip-n-saw, and pulpwood) products, manufacturing of finished wood products, use of finished wood products, and decomposition of finished wood products in landfills at the end of the useful life period. Lumber produced from sawtimber was used for single-family housing, half of the obtained chip-n-saw was used for lumber towards multi-purpose housing, and the remaining half was used for paper production. Pulpwood biomass was used only for paper production. Also, the system boundary for intercropping loblolly pine and carinata to produce both timber and bio-jet fuel is represented in Figure 2.1. It included all the stages of agricultural production of carinata, oil extraction, bio-jet fuel production, and bio-jet fuel combustion replacing petroleum-based jet fuel.

Loblolly Pine Management

We used the growth and yield model developed by Gonzalez-Benecke et al. (2011) for estimating the volume of roundwood produced in an intensively managed loblolly pine stand for site indices 15.3m, 18.3m, and 21.3m (average dominant height in meters at the 25th year of the plantation) located in the Lower Coastal Plains of South Georgia. For simulating yield of a hectare of loblolly pine plantation, we selected a mix of appropriate row spacing, tree spacing, planting density, and thinning age for both selected production scenarios (Table 2.2). For selected production systems, the fertilizer application rate of loblolly pine, the time of application, and associated emissions from fertilizer application are reported in Table 2.3. Carinata was planted during the initial six, seven, and eight years only for site indices 21.3m, 18.3m, and 15.3m, respectively. Because of disease susceptibility, carinata needs to be planted once every three years (Seepaul et al., 2019). Therefore, carinata was planted on the first, fourth, and seventh year in the intercropping system along with loblolly pine for 21, 22, and 24-years rotation period for site indices 21.3m, 18.3m, and 15.3m, respectively. Carinata was planted in a 3.7m strip between rows of loblolly pine seedlings, leaving a buffer of 1.22m at each side to minimize competition. Therefore, about 60% of the area was used for carinata production. The mean yield of carinata was 2311.02 kg/ha in South Georgia (Dr. Anderson, personal communication, April 3rd, 2020).

Table 2.2: Silvicultural management activities for loblolly pine.

Parameter		Loblolly Pine Only	Intercropping Systems
Row Spacing (m)		3	6.1
Tree Spacing (m)		2.5	1.83
Planting Density (seedlings/ha)		1333	897
Thinning Age (year)	Site Index 15.3m	17	17
	Site Index 18.3m	15	16
	Site Index 21.3m	13	14

Table 2.3: Fertilizer application rate and time for loblolly pine.

Fertilizer	Amount	Units	Time	References
Nitrogen (N)	151.32	kg/ha	Year 02	(Dickens et al., 2012)
	252.2	kg/ha	Thinning year	
GHG Intensity of N Fertilizer	4.77	kg CO_2e/kg	-	(Lal, 2004)
Phosphorus (P)	28	kg/ha	Year 02	(Dickens et al., 2012)
	28	kg/ha	Thinning year	
GHG Intensity of P Fertilizer	0.73	kg CO_2e/kg	-	(Lal, 2004)

Quantifying Carbon Sequestration in Wood Products

Timber products obtained from loblolly pine plantation during the time of harvesting were used for producing lumber and paper. The lumber obtained from chip-n-saw and sawtimber have 50% of water and 50% of dry biomass. About 50% of the dry weight of the lumber is carbon. Therefore, the total carbon present in wood products in a particular year was estimated by multiplying the amount of lumber coming out of sawtimber and chip-n-saw by 0.25 and the amount of paper coming out of pulpwood by 0.50. The carbon present in the wood products will start decaying based on their half-lives. For quantifying the carbon stored in wood products at a give year t, we used the following equation:

$$\begin{aligned} &Carbon\ in\ Wood\ Products\ (t) \\ &\quad = [Carbon\ in\ Wood\ Products\ (t) + Carbon\ in\ Wood\ Products\ (t-1)] \\ &\quad * exp\left(-\frac{LN(2)}{Halflife}\right) \end{aligned}$$

The half-life of different wood products is reported in Table 2.4. The decayed portion of the carbon stored in wood products will directly go to the landfill, where it will further divide into degradable and non-degradable portions. About 77% of carbon present in wood products from sawtimber and chip-n-saw and 44% of carbon present in paper products from pulpwood will go to non-degradable landfill portion, and the remaining amount of carbon will go to the degradable portion of the landfill (Dwivedi et al., 2012). The degradable portion of the carbon in the landfill will undergo further decay based on the half-life. Carbon will be leaked into the atmosphere from the landfill due to the decay of the degradable portion. For calculating the total carbon savings in the system boundary, we also subtracted the amount of emissions coming out of biomass production in loblolly pine plantation from the amount of carbon sequestered in the wood products and in landfills.

Table 2.4: Half-life of wood product end-use.

Product	**Half-life (years)**
Lumber for Single Family Housing	100
Lumber for Multi-Family Housing	70
Paper	2.6
Degradable fraction of landfill	14

Source: Dwivedi et al. (2012) and Skog and Nicholson (1998)

Avoided Carbon Emissions from Carinata based Bio-jet Fuel

Agricultural Production of Carinata

Carinata is a winter season oilseed crop planted between early to mid-November at the rate of 5.6 kg/ha of seed on average (Seepaul et al., 2019). Table 2.5 reports all the inputs for the cultivation of a hectare of carinata in South Georgia and the associated carbon dioxide emission reference values for each of the agricultural inputs. As 60% area of the land will be used for carinata production, the yield was reduced to 1386.61 kg/ha from the mean yield of 2311.02 kg/ha (Dr. Anderson, personal communication, April 3rd, 2020).

Table 2.5: Agricultural production input for carinata

Input	Reference Amount	Unit	CO_2 Emissions References	Unit
N fertilizer	88.92	kg/ha	4.77	kg CO_2e/kg
P fertilizer	44.46	kg/ha	0.73	kg CO_2e/kg
K fertilizer	88.92	kg/ha	0.55	kg CO_2e/kg
S fertilizer	22.23	kg/ha	2.3	kg CO_2e/kg
Herbicide use	6.37	kg/ha	23.1	kg CO_2e/kg
Fungicide use	0.93	kg/ha	14.3	kg CO_2e/kg
Insecticide use	0.69	kg/ha	18.7	kg CO_2e/kg
Desiccant use	0.14	kg/ha	23.1	kg CO_2e/kg
Diesel Usage	38.73	L/ha	2.69	kg CO_2e/L

Source: IFAS UFL (2018) and Lal (2004)

Oil Extraction Process

The oil extraction process involves several steps, i.e., seed preparation, oil extraction, and degumming (Li and Mupondwa, 2014). All the inputs needed during the oil extraction process are reported in Table 2.6. We assumed that the oil extraction stage followed the same process for canola (*Brassica napus*), and therefore, used the input data from Miller and Kumar (2013) for the carinata-based oil extraction process. In the oil extraction process, 1 kg of seed produced 0.44 kg of carinata oil and 0.56 kg of protein meal (Sieverding et al., 2016). We used mass-based allocation for quantifying the amount of dioxide carbon emissions generated for producing carinata oil.

Table 2.6: Input materials and associated carbon emissions from the oil extraction process from carinata seed

Stages	Input	Reference Amount	Unit	CO_2 Emissions References	Unit
Seed Preparation	drying heat	54.5	MJ/t seed	0.292	kg CO_2e/MJ
	Drying electricity	13.6	kWh/t seed	0.88	kg CO_2e/kWh
Oil Extraction	Electricity	40.8	kWh/t seed	0.88	kg CO_2e/kWh
	Steam	369	kg/t seed	0.126	kg CO_2e/MJ
	Cooling water	14,560	kg/t seed	0.00093	kg CO_2e/kg
	solvent (hexane)	1.94	l/t seed	17.71	kg CO_2e/l
Degumming	Electricity	2.2	kWh/t seed	0.88	kg CO_2e/kWh
	Steam	74.3	kg/t seed	0.126	kg CO_2e/MJ
	Process water	8.3	kg/t seed	0.00247	kg CO_2e/kg

Source: Miller and Kumar (2013)

Bio-jet Fuel Production Process

We followed the hydro-processed renewable fuel production pathway to produce jet fuel from carinata. Hydro-processed renewable jet (HRJ) is produced through the hydro-processing of plant oils or animal fats to create an oxygen-free automotive diesel or jet fuel (Hileman et al., 2009). Oxygen is removed through the decarboxylation pathway in which hydrogen is an essential reagent. Isomerization is also a required process that helps to achieve jet fuel properties (IATA, 2010). The system design of a simplified hydroprocessed easters and fatty acid (HEFA) production pathway is shown in Figure 2.2. Table 1.7 presents the amount of inputs to produce hydro-processed renewable jet fuel from carinata oil. In the HRJ process, 1 kg of carinata oil produced 0.71 kg of HRJ fuel (GREET, 2018). Naptha and propane mix also produced in the HRJ process as co-products. We used the mass-based allocation system to allocate carbon emissions from each of the products and co-products in the HRJ process.

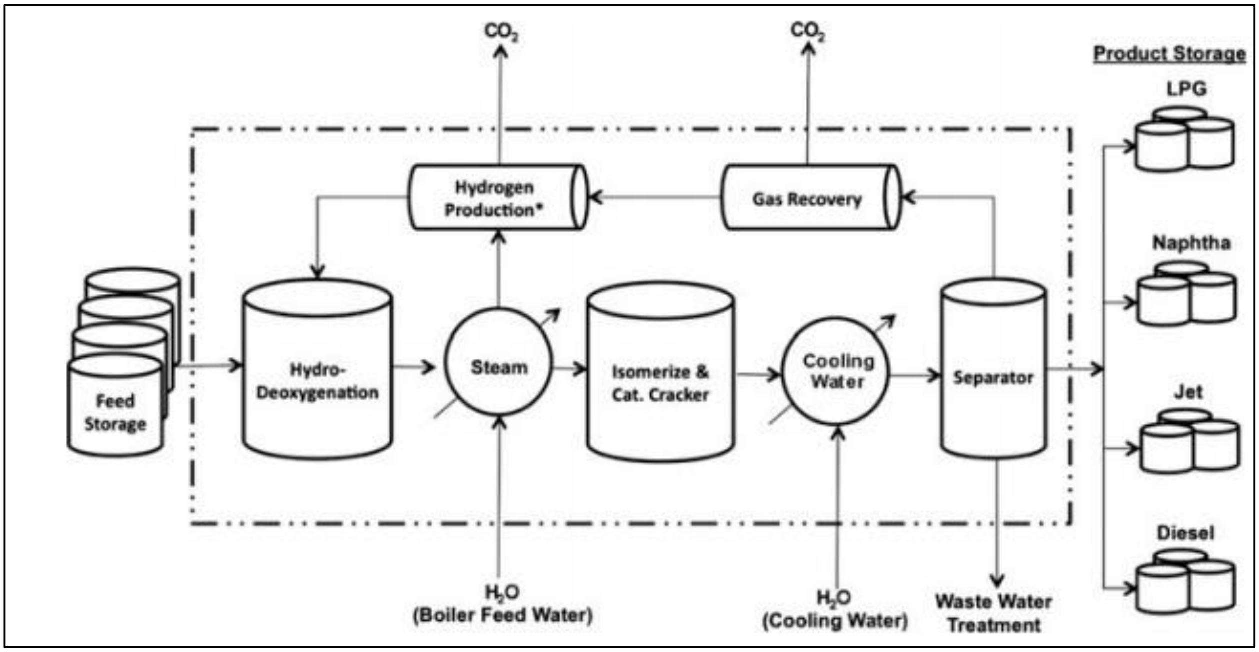

Figure 2.2: Simplified hydroprocessed esters and fatty acids (HEFA) system design. Source: Pearlson et al. (2013)

Table 2.7: Input materials and associated carbon emissions from bio-jet fuel production process from carinata oil

Input	Reference Amount	Unit	CO_2 Emissions References	Unit
H_2 use	4050.25	MJ/t of jet-fuel	0.10168	kg CO_2e/MJ
Natural Gas use	6231.7	MJ/t of jet-fuel	0.05658	kg CO_2e/MJ
Electricity use	60	kWh/t of jet-fuel	0.88	kg CO_2e/kWh

Source: GREET (2018) and Han et al. (2013)

Avoided Carbon Emissions

The consumption of conventional jet fuel emits about 2.53 kg CO_2/l into the atmosphere (US EIA, 2016). We estimated the amount of carbon emissions savings due to the use of carinata based bio-jet fuel instead of petroleum-based jet fuel for each year over a 100-years planning period. We have also calculated carbon sequestered from the residual biomass of carinata left on the ground after collecting the seeds. The mean biomass yield of carinata was 3677.94 kg/ha in South Georgia (Dr. William Anderson, personal communication, April 3rd, 2020). Finally, we calculated the total carbon saved in the intercropping system by adding emissions savings by the use of bio-jet fuel and carbon sequestered from residual biomass of carinata left on the ground and subtracted all the lifecycle emissions coming out of HRJ fuel production for each year.

Results and Discussion

Carbon in Wood Products and Landfills

Figure 2.3 illustrates the trajectory of carbon sequestration in wood production and landfill over a 100-years planning period with a 21, 23, and 24-years rotation cycle in loblolly pine only management system for site indices 21.3m, 18.3m, and 15.3m, respectively. Carbon in wood products and carbon in landfill exhibited an increasing trend over a 100-years planning period for all the site indices. The amount of total carbon stored, which also incorporated carbon emissions coming from biomass production, went down by a greater amount during every thinning and harvesting operation. Carbon stored in wood products from loblolly pine only management system over 100-years was 123.68 t (moving average 127.92 t), 111.87 t (moving average 101.08 t), and 95.62 t (moving average 77.04 t) C/ha for site indices 21.3m, 18.3m and 15.3m, respectively. Moreover, carbon stored in landfills was 140.0 t (moving average 126.05 t), 120.59 t (moving average 100.98 t), and 99.24 t (moving average 80.93 t) C/ha for site indices 21.3m, 18.3m, and

21.3m, respectively at the end of 100-years planning period. Good quality sites have higher productivity, therefore, sequesters more carbon.

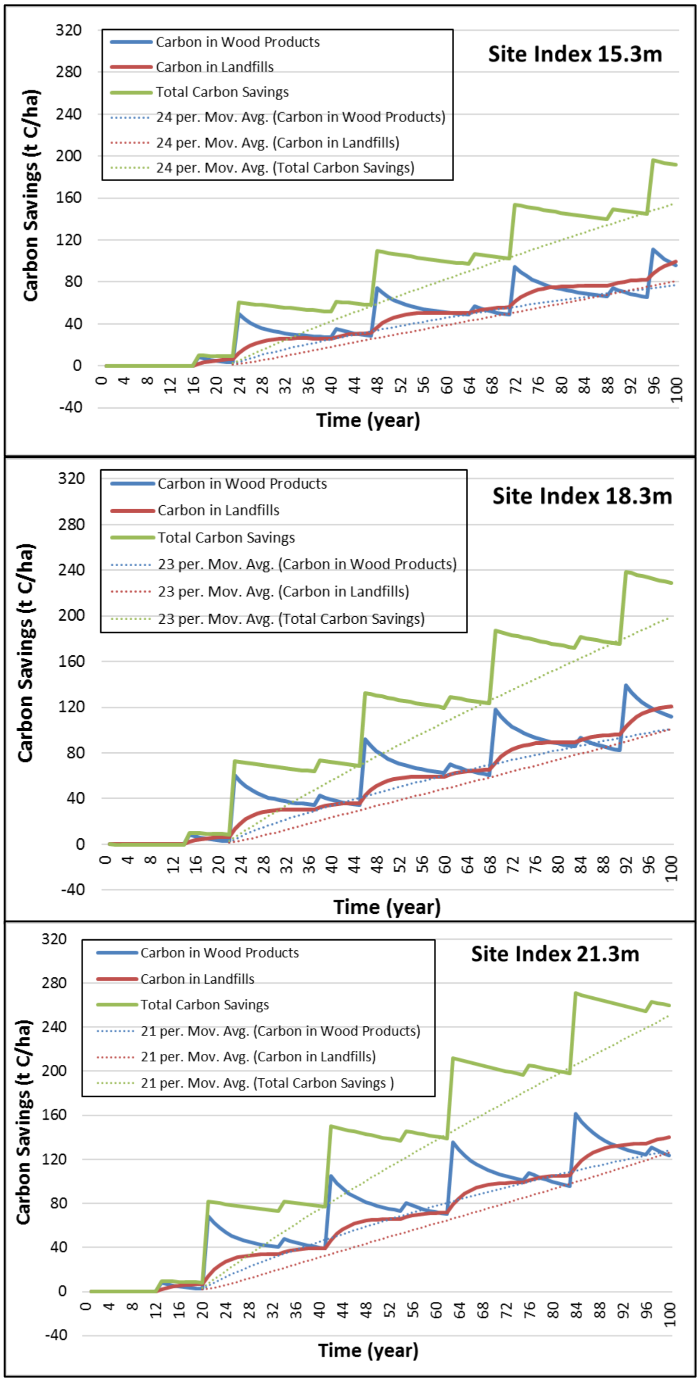

Figure 2.3: Trajectory of carbon storage in wood products and landfills over 100-years simulation period in loblolly pine only management system.

Carbon Emissions from Bio-jet Fuel Production

Farm-level production of carinata generated 136.97 kg C/ha for producing 1388.93 kg/ha of seeds. Therefore, the GHG intensity of the agricultural output was 0.099 kg C/kg of seeds. The total yield in the oil extraction process was 611.13 kg/ha, and the associated carbon emission from mass-based allocation was 88.52 kg C/ha. Therefore, the GHG intensity of the carinata oil extraction process was 0.145 kg C/kg of oil. Hydro-processed renewable jet fuel production stage produced 433.90 kg of HRJ/ha, and the amount of carbon emissions allocated to HRJ was 68.66 kg C/ha. The GHG intensity of the HRJ process was 0.158 kg C/kg of HRJ fuel. The agricultural production stage produced the highest amount of carbon emissions among the three stages of bio-jet fuel production (Figure 2.4). Fertilizer and herbicide application in the farm level production lead to the high amount of carbon emissions in this stage.

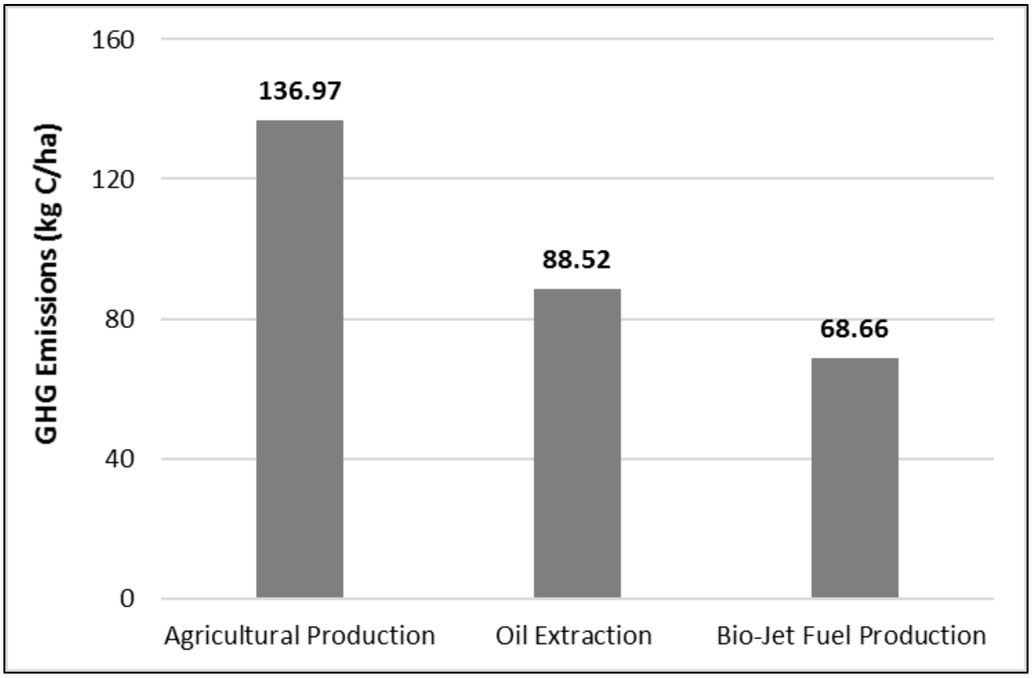

Figure 2.4: Carbon emissions related to carinata-based jet fuel production for each stage.

Carbon Sequestration from Intercropping Systems

Carbon stored in wood products followed an increasing trend over a 100-years period though the value went down during every thinning and harvesting operation in the intercropping system. However, the total amount of carbon stored in landfills after 100-years was 5.46 t, 6.75t, and 11.52 t C/ha lower than carbon in wood products based on moving averages for site indices 15.3m, 18.3m, and 21.3m, respectively. The avoided carbon emissions through the replacement of conventional jet-fuel by carinata-based bio-jet fuel remained somewhat constant over a 100-years period. Total avoided savings from carinata-based bio-jet fuel was 0.66 t, 1.29 t, and 2.15 t C/ha for site indices 21.3m, 18.3m, and 21.3m after 100-years simulation period (Figure 2.5). We made the assumption that canopy will close after six years for site index 21.3m. Avoided carbon emission was lower for site index 21.3m than the other two site indices as carinata was planted for only two rotations. Carbon storage in wood products and landfills was significantly higher than the avoided carbon savings from the replacement of conventional jet fuel with carinata-based bio-jet fuel in the intercropping system over a 100-years planning period (Figure 2.5).

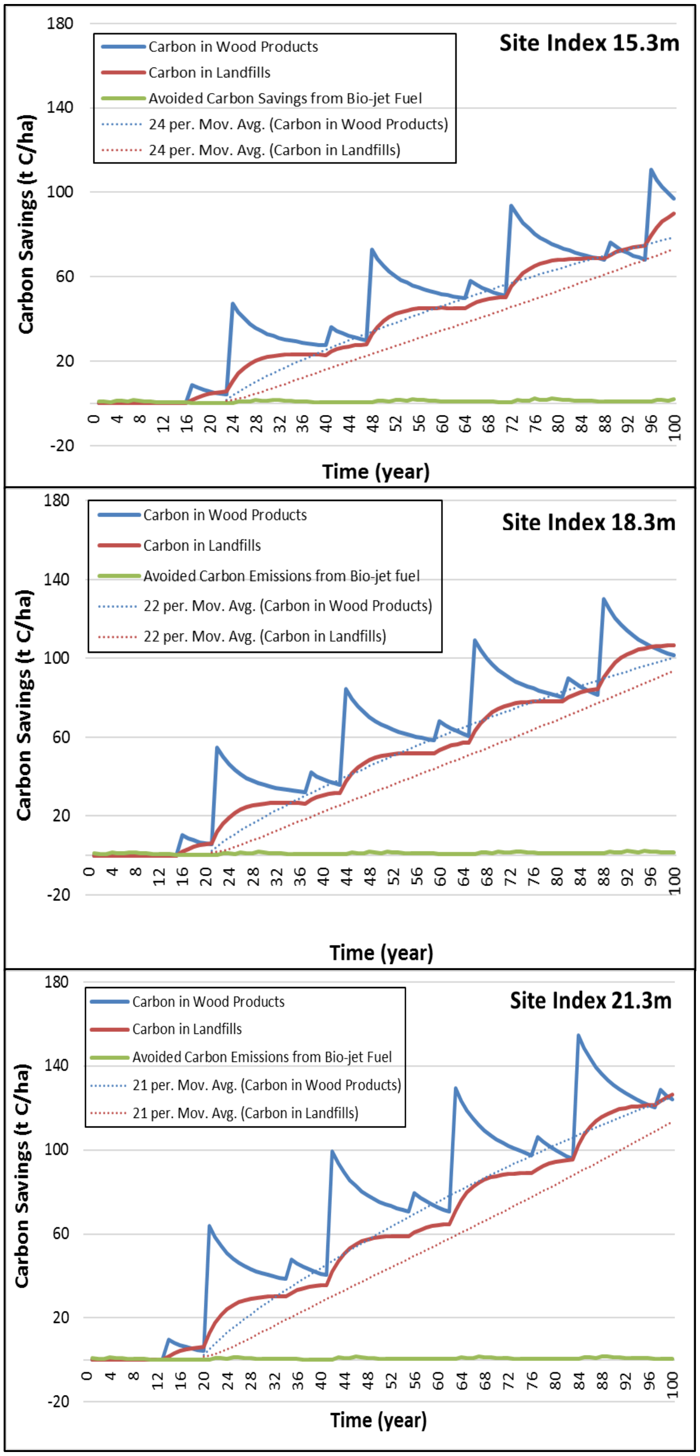

Figure 2.5: Trajectory of carbon savings from wood products and landfills and avoided carbon emissions from carinata based bio-jet fuel in intercropping systems over a 100-years simulation period.

Figure 2.6 illustrates the trajectory of carbon sequestration over a 100-years simulation period for different management systems. After every thinning and harvesting operation in both loblolly pine only management and intercropping scenario, the amount of sequestered carbon went down by a higher amount. The amount of carbon sequestered in the initial years before the thinning operation was close to zero in both intercropping and loblolly pine only management system, as no timber products (i.e., sawtimber, chip-n-saw, and pulpwood) were taken out of the stand to produce wood products until then. The total carbon sequestration from wood products and landfills and avoided carbon savings by replacing conventional jet fuel by carinata-based HRJ fuel exhibited an increasing trend over a 100-years simulation period.

Total carbon sequestered at the end of 100-years period in wood products and landfill from loblolly pine only management was 259.71 t (moving average 250.28 t), 228.97 t (moving average 198.93 t), and 191.58 t (moving average 155.21 t) C/ha for site indices 21.3m, 18.3m, and 15.3m, respectively. Oliver et al. (2014) estimated the carbon savings from different solid wood products, wood energy, and un-harvested forests through the life cycle approach and found that that efficient wood products saved more carbon than the standing forests. Whereas, the total amount of carbon sequestered in an intercropping system, which accounted for the carbon savings by the use of carinata based bio-jet fuel along with carbon storage in wood products and landfill was 14.24 t, 6.51 t, and 4.71 t C/ha lower than loblolly pine only management scenario based on moving averages for site indices 21.3m, 18.3m, and 15.3m, respectively. Lower planting density (897 seedlings/ha) can explain lower carbon savings in the intercropping system because a significant amount of the carbon savings comes from forest products. Also, carinata was planted only for two (site index 21.3m) and three (site indices 15.3m and 18.3m) rotations in each 21, 22, and 24-years cycle with constant yield, respectively. Therefore, avoided carbon savings from the replacement of conventional jet fuel with bio-jet fuel were lower, which did not compensate for the loss in carbon savings from low planting density.

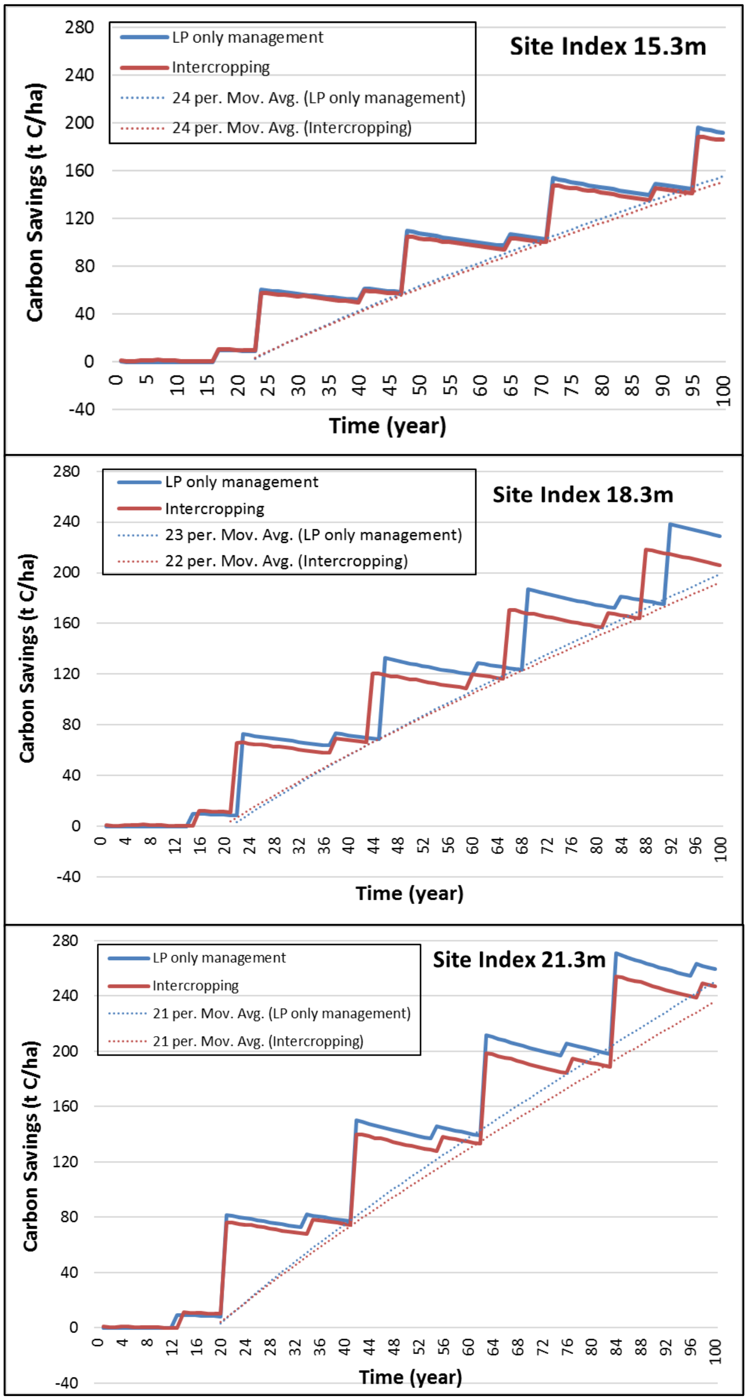

Figure 2.6: Trajectory of carbon sequestration over time in both loblolly pine only and intercropping systems.

Conclusion

We analyzed the environmental feasibility of intercropping loblolly pine with carinata oilseed crops in this study, by comparing the amount of carbon sequestered in wood products and wood present in the landfill and the avoided carbon emissions by replacing conventional jet fuel with carinata based HRJ fuel. Results from the carbon model indicate that intercropping sequestered less carbon than loblolly pine only management scenario. Devoting the forestland for an intercropping system to produce bio-jet fuel decreased the total carbon storage by 14.24 t, 6.51 t, and 4.71 t C/ha than loblolly pine only management scenario for site indices 21.3m, 18.3m, and 15.3m, respectively. A need exists to incorporate the amount of carbon sequestered in the forest stand in both production systems to understand the overall carbon sequestration process from stand to end-use of products. We hope that this study will feed into future research, with an integrated approach to mitigate climate change and establish a sustainable environment in the Southern United States.

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