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Estimating Carbon Efficiency of Bioenergy Systems in the Mississippi Alluvial Valley

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Abstract: Due to climate change and energy security concerns, bioenergy products and systems are becoming increasingly important, and Life Cycle Assessment (LCA) can provide a better understanding of their carbon efficiency. In this study, we used a cradle-to-grave LCA to analyze the carbon efficiency of a cottonwood-switchgrass agroforest system grown on agriculturally marginal soils on three sites established in 2009 in the Lower Mississippi Alluvial Valley (LMAV). A complete carbon inventory was done for both the agroforestry bioenergy system and a control cropping system that rotated soybeans and grain sorghum. Three years after establishment, the cottonwood sequestered the highest amount of carbon in dead roots, live roots, and surface residues (3222 kg ha^{-1}) and the switchgrass sequestered the highest amount of carbon in above-ground biomass (4233 kg ha^{-1}). The maximum carbon was emitted (1733 kg ha^{-1}) from the soybean/grain sorghum rotation production system. The carbon emission during production was not statistically different for the bioenergy crops. Carbon emission from both bioenergy crops were significantly different compared to traditional agricultural crops. At the end of the third growing season, cottonwood showed the best performance in the net (6.2) and gross (11.8) ratios of carbon balance. The gross ratio of carbon by switchgrass (11.6) was comparable to cottonwood, but the net ratio was approximately 50% (3.3). The net and gross ratios of carbon balance were positive for the control cropping system as well, 1.2 and 2.2 respectively. Carbon emission from the traditional agricultural production system was at least 234% higher compared to the dedicated bioenergy production system. It was evident that bioenergy crops provide a more environmentally efficient practice in terms of carbon balance than the traditional agricultural practice in the Lower Mississippi alluvial Valley.

Keywords: LCA; sustainability; bioenergy; renewable; carbon savings

1. Introduction

Emphasis on renewable energy has risen to a considerable level in the United States in recent years. This interest is primarily due to the fact that the domestic oil reserve is non-renewable and oil supply from foreign suppliers may become unstable in the future. In addition, the use of fossil fuel emits greenhouse gases (GHGs) that were out of the atmospheric cycle for millions of years which exacerbates climate change. Consequently, considerable attention has been placed on growing biomass for energy production because biofuel is a renewable resource and potentially provides a sustainable and dependable supply of energy. Biofuels are non-petroleum based fuels derived from a variety of biological sources [1,2], e.g., cellulosic biomass. In 2017, approximately 686 TWh of renewable energy was generated in the US [3], contributing 17% of the total energy generation at utility generation scale.

Among renewable energy sources, biomass contributed about 6% [3]. The percentage of total energy generation from biomass feedstock and waste biomass increased from 3% in 2004 [4] to about 6.48% in 2017 [3] of the total energy consumption. Electricity generation from renewables is projected to increase at a steady rate from 18% in 2018 to 31% in 2050 [5]. Besides contributing to the national energy supply, bioenergy also helps in creation of employment [6]. Landowners and local economies can benefit from the economic opportunities presented by bioenergy projects [7]. To increase bioenergy production and use, a number of incentive programs and subsidies have been initiated by governments [8]. Incentive programs could be helpful to increase bioenergy production, but political will would play a major role as it is the influence of forest industries on the political process that helps continue the cost-share programs [9]. There is sufficient interest among landowners to supply biomass for energy which is a positive factor in making bioenergy socially acceptable [10].

Biomass is also considered environmentally preferable compared to fossil fuel even though case-by-case evaluation of biomass as energy feedstock is recommended [11]. Managing forests for bioenergy can also improve both human and environmental health [12]. Biomass has the potential to reduce GHG, sulfur, and heavy metals emissions [13] as well as improve water quality compared to agricultural crops [14]. Co-firing biomass with coal to generate heat and electricity reduces the share of coal and avoids emission of CH_4, NO_X, and particulate matter [15] as well. The Intergovernmental Panel on Climate Change (IPCC) suggested that due to human activities, global average temperature has increased by 1 °C from 1880 to 2017 [16] and that an additional increase greater than 1.5 °C will cause catastrophic changes in climate [17]. As one of the major greenhouse gases, carbon dioxide plays a significant role in global warming. Sequestering carbon in soil, living trees and grass can be an important part of a strategy to mitigate GHG emissions and thus climate change [18,19]. Whether an agroforest-based bioenergy project is carbon efficient, i.e., if it sequesters more carbon than it emits in the environment, is a critical question. Researchers [20,21] have suggested cellulosic biomass as a carbon neutral procedure. However, assurances of such efficiency can be determined using life cycle assessment [22].

The term 'life cycle' refers to the major activities in the course of the product's lifespan from collection of raw materials, manufacture, use, and maintenance, to its final disposal [22]. Life Cycle Assessment (LCA) is a framework that evaluates all stages of a product's life assuming that they are interdependent. However, process based LCAs, while are helpful by providing a mean to account for externalities and help avoid shifting effects, may lead to truncation error if all processes and activities are not included [22,23]. LCA is a popular framework for the environmental assessment of products [24]. The Intergovernmental Panel on Climate Change [25] recommended LCA to describe the fate of stored carbon in industrial applications.

Previous LCA studies [26,27] suggested that biodiesel production and forestry related activities can reduce CO_2, CO, particulate matter, sulfur oxides emissions, and consumption of petroleum. Adler et al. [28] studied carbon sequestration efficiency of corn, soybean, alfalfa, hybrid poplar, reed canarygrass, and switchgrass. They found that hybrid poplar was the largest net GHG sink (>200 g CO_2e m^{-2} yr^{-1}) for biomass conversion to ethanol, and switchgrass was the largest GHG sink (>400 g CO_2e m^{-2} yr^{-1}) for biomass gasification for electricity generation. These estimates refer to a substantial amount of sequestration per unit area per year. Heller et al. [29] added the amount of emitted carbon dioxide after the combustion of harvested biomass in the life cycle, and concluded that the overall system contributes positively to (i.e., increases) the GWP. Liebig et al. [30] conducted a ssequestrationtudy in three states (North Dakota, South Dakota, and Nebraska) for carbon of switchgrass and observed that the harvested aboveground carbon averaged 2.5 ± 0.7 t ha^{-1} over a five-year period which is considered modest yields. However, they observed a significant increase in soil organic carbon. Zan et al. [31] conducted a study in southern Quebec, Canada using switchgrass, willow and corn (maize) and found that switchgrass sequestered significantly higher level of carbon in roots than corn. They also found that soil carbon accumulation was higher under willow than switchgrass or maize.

In the Lower Mississippi Alluvial Valley (LMAV), biomass derived from an agroforestry system, the interactive system created by combining trees and shrubs with crops and/or livestock, can potentially be more carbon efficient compared to the traditional agricultural practices of soybean and grain sorghum [32]. The LMAV has potential to sustainably grow and supply biomass for biofuel production and replace fossil fuel for energy generation. Marginal agricultural land, with virtually net zero economic profit, can be converted to produce dedicated bioenergy crop such as cottonwood and switchgrass. However, to the best of our knowledge, no study has been performed to ascertain the overall carbon balance of such a bioenergy project in the LMAV.

The primary objective of this study was to investigate the carbon efficiency of agroforest-based bioenergy projects comprised of cottonwood (*Populus deltoides*) and switchgrass (*Panicum virgatum*) in the LMAV and to compare the carbon efficiency of this system with a traditional agricultural rotation of soybean (*Glycine max*)—grain sorghum (*Sorghum bicolor*). Our goal was to identify which of these systems would perform best in terms of the carbon balance after three years of production, i.e., emit the least carbon or sequester the most carbon on a unit area basis. In order to achieve this objective, we followed the principles of LCA to make an inventory of all the activities related to the raw material collection, production, and usage (combustion in co-firing with coal) of bioenergy from these sources, estimated carbon balance of all three treatments, and calculated differences in the carbon efficiency between the treatments. The results of this study will enable policymakers to characterize the carbon trade-offs associated with cellulosic bioenergy and therefore help decide on the implementation of such projects at a mass scale in the Mississippi Alluvial Valley. The outcome may provide important insight to farmers, natural resource managers, and other energy and carbon related stakeholders on piloting such future projects.

2. Materials and Methods

2.1. Study Area

The LMAV region of the southern US has a high potential of cellulosic biomass production, since it has a long growing season and well developed agricultural industry [33]. The region is well equipped to deliver the feedstocks to processing facilities and consumer distribution points because it has significant transportation and pipeline systems [34]. These factors make the LMAV well positioned for bioenergy production. Traditionally, the marginal soils of those areas are used for soybean-grain sorghum production. An agroforest-based bioenergy study, comprised of cottonwood and switchgrass, was initiated by Liechty et al. [35] in 2009 at three locations in the LMAV:

1. The University of Arkansas Division of Agriculture Pine Tree Branch Station (PTBS) near Colt, Arkansas.
2. The University of Arkansas Division of Agriculture Southeast Research and Extension Center (SREC) in Rohwer, Arkansas.
3. The Stevenson Farm (SF) near Archibald, Louisiana (Figure 1).

At each of the three study sites, each of the three treatments—cottonwood, switchgrass, and a control treatment that consisted of annual rotation of soybeans and grain sorghum—were respectively established on 2.7, 2.7, and 1.35 ha. Whereas the control crop is annual in nature, cottonwood and switchgrass production was perennial. Switchgrass, once established, should continue production for more than 10 years [36]. In the same way, cottonwoods would regenerate from coppice after harvest, and multiple rotations could be harvested from the established stump/root systems [37]. Crops were established on marginal productivity soils with surface soil being predominantly clay at the SREC site and silt loam at the other two sites [38]. Even though the study site had homogenous and mixed plots for crops, we did not separate the results as production related activities could not be differentiated between homogeneous and mixed plots. Further details on the study area were discussed in Robinson [39] and Helton et al. [40]. Although two sites (PTBS and SF) were in active agricultural practice, surface biomass was assumed to be zero at the beginning of the site establishment. The control treatment consisted of soybeans planted in years 1 and 3, and grain sorghum in year 2 of the study on all sites.

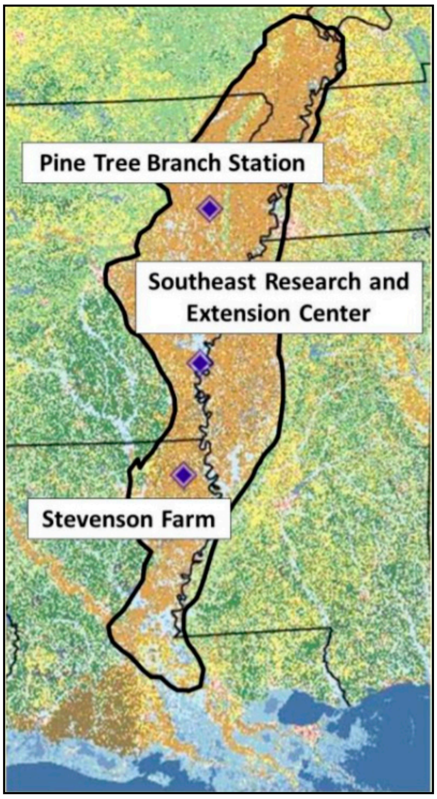

Figure 1. Study site locations [35].

2.2. *Goal Definition and Scoping*

This study was an attributional LCA in which observations were made on the flow of carbon within the chosen temporal window from raw material collection to biomass combustion for energy generation, C emissions were attributed to processes included, C sequestrations were attributed to biomass sequestered, and no other physical and economic consequences were included. The carbon balance, the ratio of C sequestration to emission, of producing biomass in a cellulosic bioenergy-based land use system were compared to a soybean/grain sorghum plantation-based land use system. The end comparison would be between carbon sequestered and emitted (kg) on 1 hectare of land between 2009 and 2012, three years after the study was initiated. It is important to mention that construction of permanent facilities such as nursery, fertilizer and herbicide production plant, drying plants, energy generating unit was not included in this analysis since the usage of those plants specific to our study were negligible compared to the total activity during the lifespan of those facilities.

2.3. *Inventory Analysis*

The major activities in the inventory were broadly categorized into three components—prior site operations, on site operations, and post-harvest operations. All these activities were carried out in the first three years in the life cycle. The harvested biomass data was for the first three years as well. The final harvest of cottonwood was done after the end of fifth year, but we collected biomass availability and carbon sequestration data after the third year to consistently compare across all treatments.

Figure 2 presents the Life Cycle Inventory (LCI) diagram. Activities that resulted in a net carbon addition to the atmosphere were given a negative sign, while those that resulted in removal were given a positive sign. The harvested dry biomass, when combusted raw for energy, emitted carbon into the atmosphere. These emissions were not considered as negative carbon release, because they began as atmospheric carbon and returned to the atmosphere after combustion.

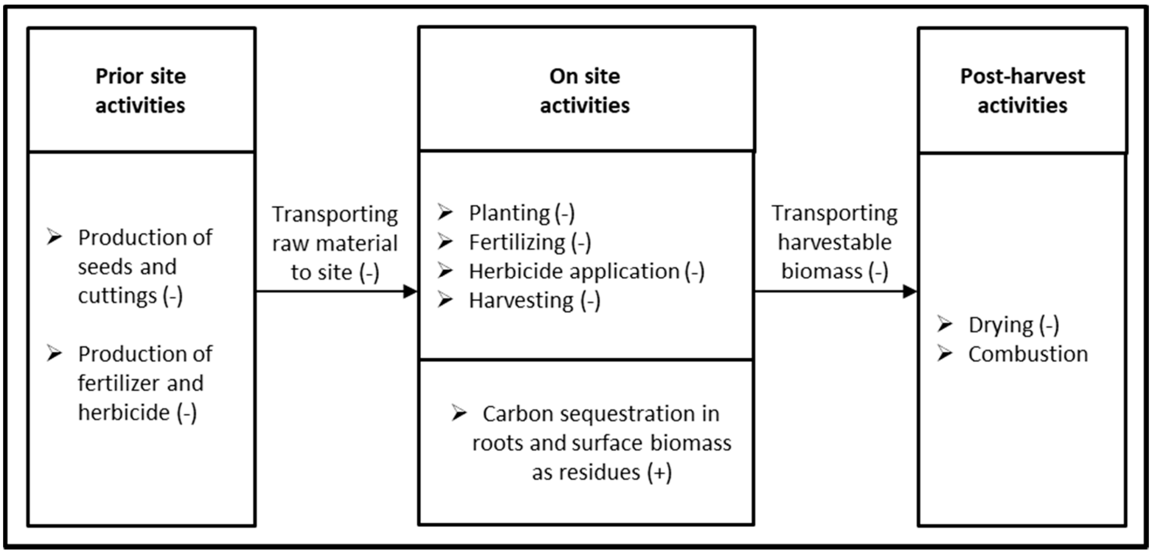

Figure 2. Carbon flow in processes included in the bioenergy system.

2.3.1. Prior Site Operations

The prior site operations stage included collection of raw materials, e.g., production of seeds and cuttings required for the planting, production of fertilizers and herbicides, and transportation of all the materials to the sites.

Seeds/Cuttings Production

Annual seed application for the control plots were 74 kg ha^{-1} of soybean seeds or 7 kg ha^{-1} of sorghum seeds. The total carbon emission of soybean and sorghum seed production is estimated using the study of West and Marland [41]. The study indicated that soybean seeds require 0.25 kg C kg^{-1} of seeds and sorghum seeds require 0.86 kg C kg^{-1} of seed. For switchgrass seeds, carbon emission was assumed to be 0.55 kg per kg of seed, which is the average of soybean and sorghum seed production. Switchgrass seeding rate was 11.2 kg ha^{-1}. For cottonwood, 4485 cuttings were planted in each hectare. Information related to carbon emissions by the cottonwood cuttings were collected from Louisiana State Nursery, where 1000 cuttings hour^{-1} are harvested using 60 horsepower engines. Primary data on the type of machines and chemicals needed for those operations were provided by the nursery as well electricity usage, fuel usage, and machine time. Degrading factor and building construction costs were assumed as negligible and not included in the analysis. Carbon emission from cutting production was calculated using Equation (1)

$$GHG_{MACHINE} = ASAE * CD * HP * T \quad (1)$$

where $GHG_{MACHINE}$ (kg CE) was the estimated carbon release for an operation, $ASAE$ was the ASAE (American Society of Agricultural Engineers) constant to estimate the fuel usage by diesel engines in a unit time, 0.227 L h^{-1} [42]; CD was the EPA conversion factor to find the carbon content in diesel fuel, 0.736 kg CE L^{-1} [43], HP is the horsepower of engine for the particular operation, and T was the duration of the operation in hours.

Fertilizer and Herbicide Production

We included carbon emission from the production processes of herbicides and fertilizers used for crop production. All fertilizers were categorized by their active ingredients—N, P, K, and lime. Information on the amount of fertilizer and herbicides applied in this study can be found in the supporting information (Tables S1–S4). We used conversion factors from Lal [44] to convert these inputs into carbon emissions (kg CE).

Transportation of Site Prep Materials

For transportation of site preparation materials such as seeds/cuttings, fertilizer, and herbicide, trucks with 250 hp engines were used with an assumed transportation distance of one hour round trip. Total transport duration for cottonwood was 6 h for cottonwood and switchgrass in each site, except for switchgrass in SREC. Switchgrass seeds were brought 5-times in the SREC site for spring and fall plantings, as establishment failed 4-times in the first two years. Therefore, transport duration was considered to be 30 h for this site. For soybean/grain sorghum rotation, since transportation occurred annually, total transportation duration was 18 h. Since site prep material was only 1/15th of the total cargo, we only attributed 1/15th of the emissions to individual transportation. Carbon emission from these transportation activities were calculated using Equation (1).

2.3.2. On Site Operations

On-site operations included planting, fertilization, application of herbicides, and harvesting of biomass. In general, 225 horsepower engines were used for ripping soil or tillage operations to prepare the site. As switchgrass establishment at the SREC failed in the first four attempts, planting activities for switchgrass were carried out five times. For planting cottonwood, 100 horsepower engines were used. Machine horsepower varied between 80 and 225 to plant switchgrass and soybean/sorghum. For herbicide and fertilizer application, 80 to 100 horsepower engines were used in most cases. No fertilization was performed for the switchgrass in SREC site since switchgrass was not established until the third growing season. Cottonwood was harvested using 88 horsepower engines while switchgrass and soybean/grain sorghum harvesting was done using various horsepower engines ranging from 80 to 240 for switchgrass and 88 horsepower engines for cottonwood. There were three harvesting operations for the soybean/grain sorghum rotation during the three-year study. Switchgrass was only harvested at the end of the last two growing season, except at the SREC site. Approximately 7.6 cm of stubble was left after each harvesting of switchgrass. However, that stubble was not harvestable and was not included in the analysis. Equipment degrading factor was not accounted assuming it was insignificant. A summary of horsepower engines and durations related data for all on-site activities are presented in the supporting information (Table S5). More detailed and specific data relating to each site and crop are reported in the supporting information as well (Tables S6–S9).

Carbon emission from all these applications was calculated using Equation (1), except for cottonwood harvesting operation, for which fuel usage information was used in Equation (2)

$$GHG_{FUEL} = C_{Fuel} * Fuel \tag{2}$$

where GHG_{FUEL} was the amount of carbon emitted (kg); C_{Fuel} was the amount carbon present in diesel fuel (0.734 kg C L^{-1} [43]; and *Fuel* was the amount of fuel consumed in liters. Approximately 151 L of fuel (55.93 L ha^{-1}) was used in PTBS for harvesting and the same amount was assumed for other two sites. As mentioned before, this was a high estimate due to the highest survival in this site.

2.3.3. Post-Harvest Operations

Harvested biomass was assumed to be taken to the processing site, 100 km away with an emission rate 0.0522 kg CE t^{-1} km^{-1} [43]. The quantity of transported biomass can be calculated by adding the moisture content, obtained from literature, with the dry biomass quantity in our study. Cottonwood moisture content was 50% during harvest [45]. Switchgrass biomass naturally dried in the field and the moisture content declined to 20% before transporting it to the processing site to convert it to oven dried biomass [46]. Soybean/grain sorghum moisture content was 20%, similar to switchgrass, during harvest [47]. Carbon emission from drying biomass was 2.07 kg C t^{-1} of dried biomass [48]. We did not include any additional processing such as torrefaction, an anaerobic thermochemical process, which allows torrefied feedstock to completely replace coal in the power plant by increasing the energy density [49]. Not using torrefaction would limit the share of biomass in co-firing to 15% without loss of thermal efficiency [50].

Carbon Estimation in Biomass

Harvestable biomass of cottonwood was oven dried and C content of dried biomass was calculated using a factor of 0.5 [51]. Carbon concentrations in all other biomass were determined in the laboratory and the methods associated with these determinations can be found in Liechty et al. [35] and Helton et al. [40]. Surface residue was sampled from cottonwood and soybean/grain sorghum rotation plots, but not from the switchgrass plots. Surface residue referred to the harvesting residue from the soybean/grain sorghum rotation, and leaf and plant litter from the cottonwood plots. These samples came from the plots where maximum survival occurred, and therefore are the highest estimates.

2.4. Carbon Efficiency Ratio

Valuation of sequestered carbon was accomplished through estimates of three-year carbon addition to both the aboveground and belowground systems in each treatment. The above ground system indicated the harvested shoot system of the plants. The sum of the carbon below the ground fine roots and surface residues is referred to as total carbon sequestered in Equations (3) and (4).

$$Net\ ratio\ of\ carbon = \frac{\text{Total carbon sequestered on site}}{\text{Total carbon added into the atmosphere}} \tag{3}$$

$$Gross\ ratio\ of\ carbon = \frac{\text{Total carbon sequestered on site} + \text{carbon in harvested biomass}}{\text{Total carbon added into the atmosphere}} \tag{4}$$

Any net ratio above 1 meant the system was carbon negative and sequesters more carbon than it emits during production. If the net ratio was between 0 and 1, the system would not be considered for permanent sequestration. Any gross ratio above 1 meant the system was efficient for biomass production. It was hypothesized that the bioenergy system would retain a net ratio above 1.

2.5. Statistical Analysis

Wilcoxon signed rank tests were conducted to test whether the carbon emissions (kg/ha) from all three feedstocks were significantly different. We had 11 emissions data from 11 activities within each treatment averaged across all three sites which were compared pairwise. We performed this test instead of paired Student's t-test since distribution of difference between two sample means cannot be assumed as normally distributed. We compared cottonwood with switchgrass, cottonwood with soybean/grain sorghum, and switchgrass with soybean/grain sorghum. Null hypotheses for the tests were that emissions were not different. Analyses were performed using the Stata/IC 12.0.

2.6. Sensitivity Analysis

Three scenarios were considered for the sensitivity analysis to understand the degree of carbon efficiency. These scenarios provided an idea on how certain factors related to the system can vary within the defined window.

2.6.1. Scenario 1; Better Switchgrass Production

This scenario assumed that the switchgrass production at the SREC site was not hampered. The switchgrass estimates for carbon emission, sequestration, and biomass harvested from the PTBS site were used to estimate these values for the SREC site as well as to calculate the net and gross carbon ratios.

2.6.2. Scenario 2; Carbon Emission from the Combustion of Harvested Biomass

Heller et al. [29] found negative carbon potential when carbon from the combustion of biomass was added as emission. In this scenario, ratios were calculated with the following formula,

$$Gross\ ratio\ of\ carbon = \frac{\text{Total carbon sequestered on site} + \text{carbon in harvestable biomass}}{\text{Carbon emission} + \text{emissions from biomass combustion}} \quad (5)$$

2.6.3. Scenario 3; Risk Analysis

We allowed all carbon emissions coming from the inputs related to the production of crops such as fertilizer, herbicides, fuels required to vary within 10% deviation around their respective means. In addition, we allowed biomass yields and sequestration in roots and surface biomass to vary within the same range as emissions. We ran the simulation for 10,000 iterations using Monte Carlo simulation with @Risk software by Palisade Corporations (www.palisade.com/risk).

3. Results

In site PTBS, the growth of both cottonwood and switchgrass was about two meters in height, which is poor for cottonwood and excellent for the switchgrass. At the end of the third growing season, a total of 4.1 and 18.5 t ha^{-1} of oven dry biomass (Table 1) was produced by cottonwood and switchgrass respectively [52]. The production values were considered poor for cottonwood and excellent for the switchgrass.

Table 1. Amount of harvested biomass in all three sites during three years of study.

	Cottonwood	Switchgrass	Soybean/Sorghum
		dry kg ha^{-1}	
PTBS	4126	18,503	4719
SREC	7516	0	5949
SF	5922	10,181	770
Average	5855	9561	3813

In study site 2, SREC, switchgrass was not established until the growing season of year three. Hard frost and sustained flooding inhibited switchgrass establishment in year one and year two, respectively. Therefore, no switchgrass was harvested from this site. When we performed our overall carbon balance analysis, we did include zero harvest for switchgrass from SREC and calculated the mean production accordingly. The cottonwood trees were among the tallest of any site, averaging 4 to 5 m in height. The average above ground biomass for cottonwood was 7.5 oven dry t ha^{-1} at this site.

Study site 3, SF, was in Richland Parish, Louisiana. The plots containing cottonwood trees characterized by moderate mortality. On average, trees were 3 m in height with abundant grass cover in the understory after the third growing season. Following the third growing season, the above ground biomass for cottonwood and switchgrass was 5.9 and 10.2 oven dry t ha^{-1}, respectively.

3.1. Carbon Emission

Considering included activities during the first three years of production, the soybean/grain sorghum rotation emitted the highest amount of carbon (Table 2). Between the two bioenergy crops, cottonwood production processes emitted approximately 1.3% (7 kg C ha^{-1}) more carbon compared to production of switchgrass. Cottonwood cuttings production for initial planting emitted 46 kg C ha^{-1}. Soybean and sorghum seed production for one annual planting emitted 18.5 kg C ha^{-1} and 6.02 kg C ha^{-1}, respectively. Since we had two rotations of soybean and one rotation of sorghum, production of seeds for these crops emitted a total of 43 kg C ha^{-1} in first three years of production. Since the traditional control crop was of annual nature and bioenergy crops are of perennial nature, activities such as production and transportation of site preparation materials such as seeds/cuttings, fertilizer, herbicide, and site preparation were repeated for the control crop, but performed only once for the bioenergy crops. Therefore, C emissions, per unit area, from all these activities were understandably higher for the control crop compared to the bioenergy crops.

Table 2. Total carbon emitted from each crop during the first three years in the life cycle, averaged across three sites.

Activities	Cottonwood	Switchgrass	Soybean/Grain Sorghum
	kg C ha^{-1} (%)		
Seeds/Cuttings	45.8 (8.8%)	14.4 (2.8%)	43 (2.5%)
Production of fertilizers	45.9 (8.8%)	71.2 (13.9%)	660.4 (38.1%)
Production of herbicides	73.3 (14.1%)	27.4 (5.3%)	198.1 (11.4%)
Transportation of site preparation materials	6.3 (1.2%)	14.7 (2.9%)	37.8 (2.2%)
Site preparation	58.4 (11.2%)	62.9 (12.3%)	274.4 (15.8%)
Planting	75.6 (14.6%)	118.1 (23.0%)	122.7 (7.1%)
Fertilization	26.1 (5.0%)	22.3 (4.4%)	89.4 (5.2%)
Herbicide application	64.2 12.4%)	29.4 (5.7%)	161.8 (9.3%)
Harvesting	41.4 (8.0%)	60.5 (11.8%)	108.8 (6.3%)
Transportation of harvested biomass	70.3 (13.5%)	71.7 (14.0%)	28.6 (1.7%)
Drying	12.12 (2.33%)	19.79 (3.9%)	7.89 (0.5%)
Total	**519.5 (100%)**	**512.4 (100%)**	**1732.9 (100%)**

Emissions from switchgrass exceeded cottonwood in transportation of site preparation materials, site preparation, and planting because there were multiple attempts to establish switchgrass in site SREC. There was no fertilization activity for switchgrass in SREC. Otherwise, the emissions from fertilization for switchgrass would have exceeded emissions from fertilization for cottonwood. Cottonwood was fertilized only once in the third year of the establishment which explains the lower percentage share of emissions.

Emission from transportation of harvested biomass was proportional to the yield of green biomass over the three years of study period. Despite having no switchgrass harvest from the site SREC, average biomass production from all three sites was highest for switchgrass. Therefore, transportation of switchgrass emitted the highest amount of carbon (71 kg C ha^{-1}) among all three treatments. Moisture content in green biomass played an important role in emission from transportation. Even though switchgrass dry biomass was 63% higher compared to cottonwood, their emission from transportation were almost similar. This is due to the higher moisture content in cottonwood green biomass (50%) compared to switchgrass (20%). Harvested biomass transportation was the second highest emission category for switchgrass. It is our understanding that it would have been the highest category if multiple planting efforts were not required in site SREC.

Beyond the three years of our study period, only harvesting activity and transportation of harvested biomass would be repeated for the bioenergy crops, given their perennial and regenerative nature. Some additional replanting and fertilization activities can be performed if necessary, i.e., if mortality occurs. Since most activities would not be repeated for bioenergy crops for subsequent years, but would be repeated for the control crop, difference in the overall C emission between bioenergy crop and control crop is only likely to increase over the years.

3.2. Carbon Sequestration

Carbon in the roots and surface residue was considered sequestered. We first report the total biomass accumulated in roots and surface residue over the three years of our planning horizon across all three sites (Table 3) and then report the carbon in those accumulated biomass (Table 4). Switchgrass sequestered the highest amount of biomass in live roots in site PTBS and SF. In addition, at both sites, switchgrass sequestered more biomass in dead roots compared to cottonwood. However, soybean/grain sorghum accumulated the most biomass in dead roots, higher than the bioenergy crops.

Table 3. Total biomass (dry, kg ha^{-1}) accumulated by fine roots, dead roots, and surface biomass as residue during the first three years.

		Live Roots	Dead Roots	Surface Biomass	Total
	Study Site		kg/hectare		
Cottonwood	PTBS	1768.39	1528.92	4562.91	7860.22
	SREC	2575.22	1471.81	5000.94	9047.97
	SF	1177.08	659.46	10,737.02	12,573.56
	AVERAGE	**1840.23**	**1220.07**	**6766.95**	**9827.25**
Switchgrass	PTBS	5063.85	1866.02	0.00	6929.87
	SREC	0.00	0.00	0.00	0.00
	SF	3323.10	3079.94	0.00	6403.04
	AVERAGE	**2795.65**	**1648.65**	**0.00**	**4444.30**
Soybean/Sorghum	PTBS	132.63	4163.08	1802.58	6098.29
	SREC	208.15	2591.79	2646.50	5446.45
	SF	819.72	2466.53	1347.93	4634.18
	AVERAGE	**386.83**	**3073.80**	**1932.34**	**5392.98**

Table 4. Carbon (kg C ha^{-1}) sequestration on site by live roots, dead roots, and surface biomass as residue (not harvestable tree biomass) after the first three years.

		Live Roots	Dead Roots	Surface Biomass	Total
	Study Site		kg/hectare		
Cottonwood	PTBS	744.60	546.26	1424.83	2715.70
	SREC	1052.15	513.32	1359.13	2924.60
	SF	452.80	209.50	3362.15	4024.44
	AVERAGE	**749.85**	**423.02**	**2048.71**	**3221.58**
Switchgrass	PTBS	2060.66	618.59	0.00	2679.25
	SREC	0.00	0.00	0.00	0.00
	SF	1323.44	1069.89	0.00	2393.33
	AVERAGE	**1128.03**	**562.83**	**0.00**	**1690.86**
Soybean/Sorghum	PTBS	50.53	1335.20	810.69	2196.43
	SREC	73.65	855.55	1160.22	2089.42
	SF	320.56	879.70	619.71	1819.97
	AVERAGE	**148.25**	**1023.49**	**863.54**	**2035.27**

Cottonwood sequestered a greater amount of total biomass, and carbon, in the combined roots and residues pools than either of the other two treatments. Leaves and twigs comprised the major component of the cottonwood residues. Since we assumed that the stubble left in the field after harvesting switchgrass was negligible, we report no surface residue for switchgrass, and therefore, no carbon sequestered in surface residue for this crop. Surface residues from the crop rotation was relatively high as only the food parts were harvested and the stover, which is the leaves and stalks of field crops, was left on site. However, in this case, the important amount was the live roots, because they will continue to keep the carbon on site whereas the surface carbon and dead roots will gradually decay.

Switchgrass sequestered the highest amount of carbon in the above ground shoot system (Figure 3) in three years, averaged across all three sites, even though there was no harvest in site SREC. This is because harvest from switchgrass in PTBS well compensated for the lack of harvest in SREC. Perhaps the silt loam soil in PTBS was better suited for switchgrass production. Aboveground biomass production for cottonwood, switchgrass, and soybean/grain sorghum rotation was 5.9, 9.6, and 3.8 t ha^{-1} respectively, averaged across sites. For the LCA of carbon, all this biomass was assumed to be harvested and transported to a production facility for conversion to energy. Therefore, no carbon other than that in the root system and surface residue was considered to be sequestered on site. The amount of carbon harvested from switchgrass was about 1.45-times and 2.35-times greater than the amounts of carbon harvested from the cottonwood or the soybean/grain sorghum rotation.

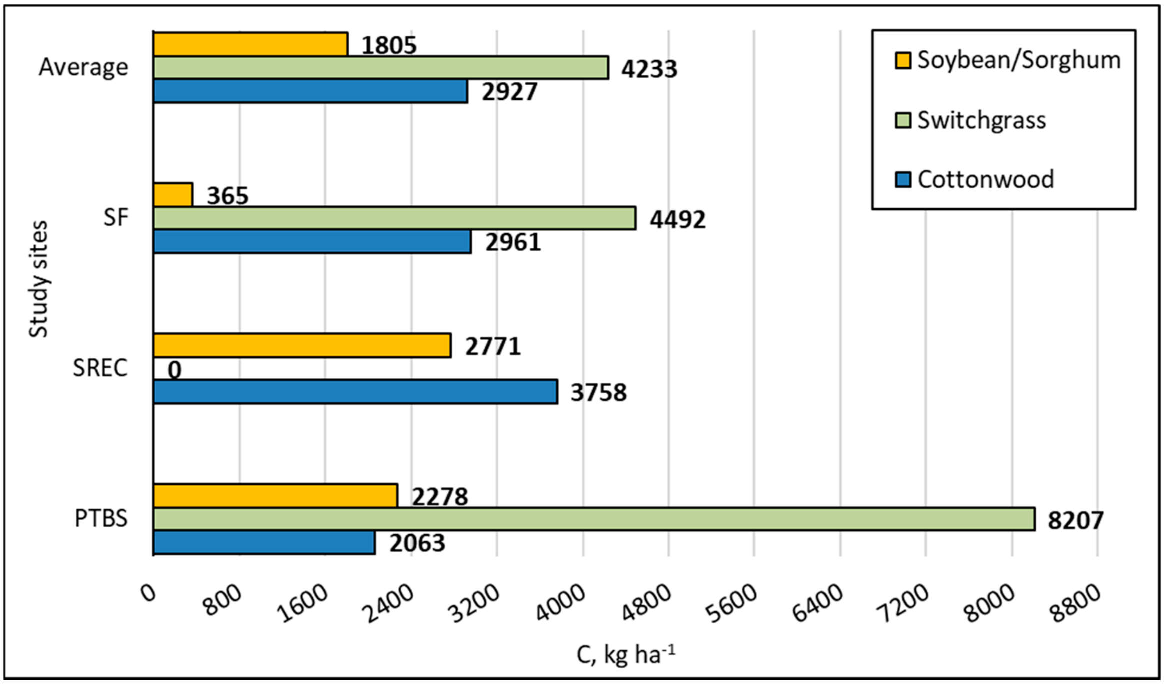

Figure 3. Total carbon (kg ha^{-1}) stored in the harvestable biomass in all three sites at the end of three years.

The average annual carbon sequestration by switchgrass was 1.1 t ha^{-1} year^{-1} (43%) lower than the sequestration reported by [30]. This was because there was no harvest from the SREC site during the study. C sequestration in site PTBS was comparable, approximately 9% higher, to their study. In addition, their study was conducted for five years. Potential changes in soil organic carbon were not included in the analysis but could alter the total amounts of C sequestered by each crop.

3.3. Carbon Efficiency Ratio

On an average across sites, a total of 3222 kg C ha^{-1} was sequestered by cottonwood in the live roots, dead roots, and surface residues (Table 5). The net ratio of carbon balance was 6.2, which meant that the amount of carbon sequestered in live roots, dead roots, and surface residues was approximately 6.2 times more than carbon emitted for producing cottonwood. When the carbon in the harvested biomass was added to the carbon sequestered in site, the gross ratio of the carbon balance was approximately 12, indicating that the total gross carbon sequestered in both the root and shoot system was 12-times more than emitted carbon. We report gross ratio of carbon balance, because it includes carbon in harvested biomass and that is important from the perspective of replacing geologic carbon.

Table 5. Total C sequestered, amount of harvested carbon, total carbon emitted, and the net and gross ratio of carbon efficiency after three years for each site and treatment.

Site	Treatment	Carbon Sequestered on Site S (kg ha^{-1})	Amount of Harvested Carbon H (kg ha^{-1})	Carbon Emitted during Production E (kg ha^{-1})	Net Ratio of Carbon Balance S/E	Gross Ratio of Carbon Balance (S + H)/E
PTBS	Cottonwood	2716	2063	541	5.02	8.83
	Switchgrass	2679	8207	563	4.76	19.33
	Soybean/Grain Sorghum	2196	2278	1260	1.74	3.55
SREC	Cottonwood	2925	3758	484	6.04	13.80
	Switchgrass	0	0	576	0.00	0.00
	Soybean/Grain Sorghum	2089	2771	2456	0.85	1.98
SF	Cottonwood	4024	2961	533	7.55	13.11
	Switchgrass	2393	4492	527	4.54	13.07
	Soybean/Grain Sorghum	1820	365	1535	1.19	1.42
Average	Cottonwood	3222	2927	519	6.20	11.84
	Switchgrass	1691	4233	512	3.30	11.56
	Soybean/Grain Sorghum	2035	1805	1733	1.17	2.22

The net and gross ratio of carbon balance from switchgrass was 3.3 and 11.6, respectively. On the other hand, the traditional agricultural crop's net and gross ratios were 1.2 and 2.2, respectively. Both bioenergy crops were more efficient in carbon balance ratio compared to the agricultural crop. The net ratio is approximately 88% to 428% greater for cottonwood compared to switchgrass and traditional agricultural crop, respectively; the gross ratio is approximately 2.4% and 434% greater, respectively. Therefore, among our three treatments, cottonwood was the most efficient crop as a net carbon sink.

The net ratio for cottonwood was the highest in site SF because of the highest carbon sequestration on site. However, gross ratio was the highest in site SREC because of the highest carbon sequestered in harvestable biomass. Site PTBS showed the best results for switchgrass, in both net and gross ratio, primarily because of the difference in harvestable biomass. This emphasizes the importance of selecting between bioenergy crops based on overall climatic condition to maximize the overall carbon balance.

Similar to the findings of other studies for corn [28,53,54], the net ratio of sequestered carbon for the row crop system used in our study (soybean/grain sorghum rotation) was greater than 1. Bioenergy crops being more carbon efficient than soybean-grain sorghum rotation is supported by other studies [28,55] as well. However, for long term sequestration and to keep the carbon efficiency valid by making the sink permanent, the system has to continue [24]. In other words, if we are to keep these amounts of carbon out of the atmosphere permanently, the agroforestry system needs to remain active and cannot be abandoned. Otherwise, the soil organic carbon might decay into the atmosphere if plots are left unused after harvest.

3.4. Wilcoxon Signed Rank Test for Emissions

Carbon emissions from different activities were compared for the different treatments on all three sites. Since the sample sizes were small and the data were not normally distributed, pairwise comparisons using Wilcoxon signed rank test was performed. Average carbon emissions from bioenergy crops were significantly different when compared to the traditional agricultural crops (Table 6). However, no significant difference was observed between the bioenergy crops. This implies that the bioenergy crops emitted significantly lower carbon in the production process than the traditional agricultural crops.

Table 6. Statistical analysis of average carbon emissions from activities for all three sites.

Hypothesis: Mean 1 − Mean 2 = 0	Significance (Prob > $|z|$)
Cottonwood (1), Switchgrass (2)	Not significant (0.79)
Cottonwood (1), Soybean/Grain Sorghum (2)	Significant (0.02)
Switchgrass (1), Soybean/Grain Sorghum (2)	Significant (0.02)

3.5. Sensitivity Analysis

3.5.1. Scenario 1; Better Switchgrass Production

When switchgrass data for SREC was replaced with PTBS data, the average net ratio of carbon sequestration to emission by switchgrass in all three sites improved from 3.3 to 5.4, and the gross ratio improved from 11.6 to 19.9. The gross ratio of carbon balance for switchgrass became highest, surpassing cottonwood, as the average harvested biomass for switchgrass across sites increased from 4233 to 6969 kg ha^{-1} site^{-1}. Total carbon emitted was reduced from 512 to 480 kg ha^{-1} site^{-1}. To summarize, the net and gross ratio of carbon balance for switchgrass increased by approximately 63% and 72%, respectively.

3.5.2. Scenario 2; Carbon Emission from the Combustion of Harvested Biomass

Our primary analysis did not consider carbon emission into the atmosphere from the combustion of harvested biomass for energy. We argued that it was reasonable since the released carbon was captured from the atmosphere to begin with. However, Heller et al. [29] assumed simple combustion for energy (electric) generation as well and added C emissions from combustion to calculate gross ratio of carbon efficiency. This approach is considered to be more conservative in terms of calculating carbon balance. They found the gross ratio to be less than 1 which indicates negative carbon balance. Contrary to their findings, we found positive gross ratio for all three crops (Table 7).

Table 7. Gross ratio of carbon production when emission from the combustion of harvestable biomass is included (using the procedure described by Heller et al. [29]).

Treatment	Carbon Sequestered on Site S (kg ha^{-1})	Amount of Harvested Carbon H (kg ha^{-1})	Carbon Emitted during Production E (kg ha^{-1})	Gross Ratio of Carbon Balance (S + H)/(E + H)
Cottonwood	3222	2927	519	1.78
Switchgrass	1691	4233	512	1.25
Soybean/Grain Sorghum	2035	1805	1733	1.09

In this scenario, even when emission from biomass combustion were included as described by Heller et al. [29], gross ratios for sequestered carbon were approximately 1.8, 1.3, and 1.1 for cottonwood, switchgrass, and soybean/grain sorghum rotation respectively.

3.5.3. Scenario 3; Risk Analysis

When carbon from all inputs and outputs were allowed to vary within 10% deviation around the mean, net ratio of carbon balance varied between 5.3 and 7.2 for cottonwood within two standard deviations (Figure 4a). The net ratio for switchgrass varied between 2.8 and 3.9, and it varied between 1 and 1.4 for soybean/grain sorghum rotation. There was no overlap for net ratio between the crop, suggesting that there is a distinct difference in the overall carbon balance between crops.

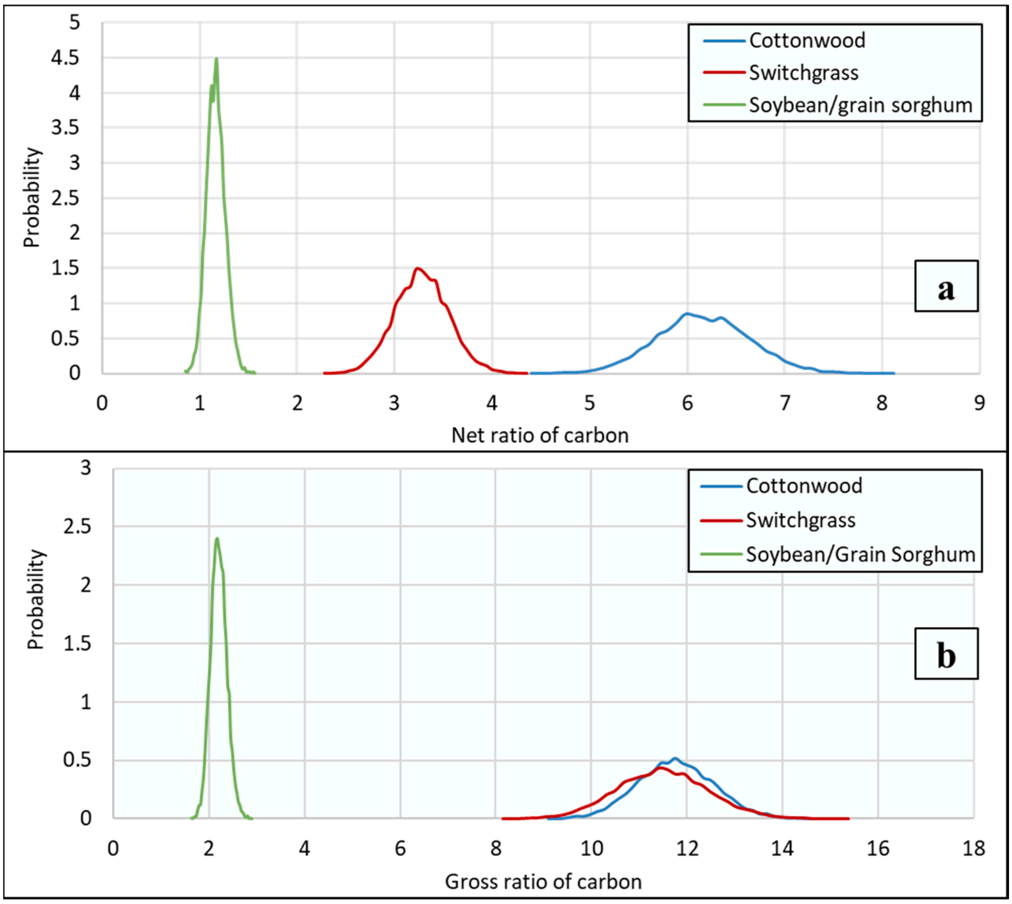

Figure 4. Sensitivity analysis of (**a**) net and (**b**) gross ratio of carbon sequestration to emission.

After including carbon sequestered in harvested biomass (Figure 4b), we found that cottonwood and switchgrass overlapped, which suggests that these two bioenergy crops may not be statistically different than each other in terms of gross ratio of carbon balance. However, bioenergy crops did not overlap with soybean/grain sorghum rotation, neither in net nor in gross ratio.

Sequestration in surface biomass was the most influencing factor in net ratio of carbon balance for cottonwood and the second most influencing factor for soybean/grain sorghum ratio, and no surface biomass was considered for switchgrass (Figure 5). Sequestration in live roots played an important role in net ratio of dedicated bioenergy crops as the most significant factor for switchgrass and the second most significant factor for cottonwood. However, it was comparatively less significant for soybean/grain sorghum as the seventh most contributing factor. Sequestration in dead roots were the most contributing factor for switchgrass and the second most contributing factor for soybean/grain sorghum's net ratio of carbon balance. For emission related factors, fertilizer was the most significant for soybean/grain sorghum rotation, whereas planting operations were the most significant for both bioenergy crops.

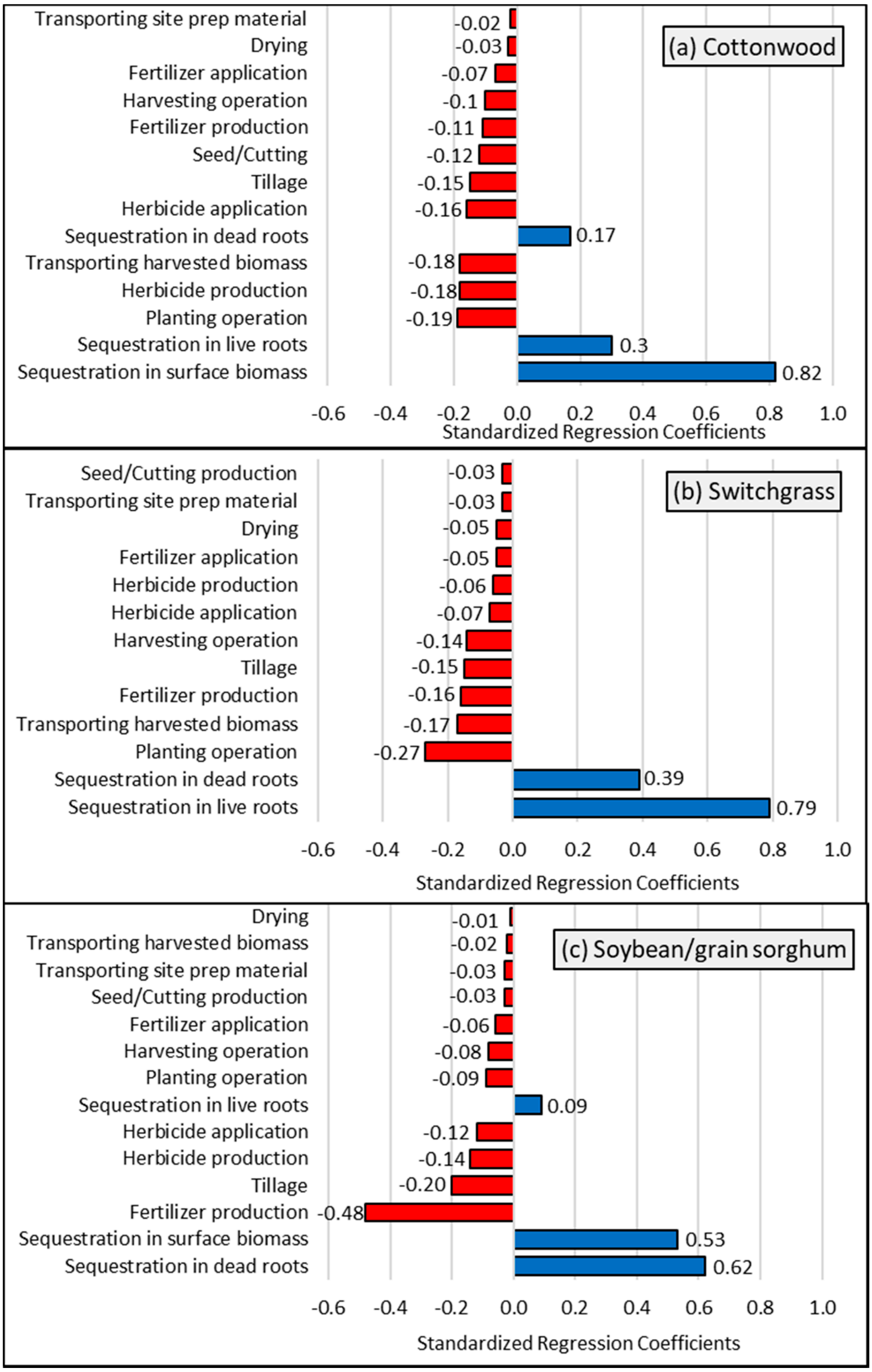

Figure 5. Standardized regression coefficients for net ratio of carbon sequestration to emission.

4. Conclusions

Fossil fuel usage in energy generation is one of the most critical sources of carbon emission, which exacerbates global warming. Bioenergy can create a renewable alternative for fossil fuel and reduce carbon emission in the process. This study answered a critical question related to the carbon efficiency of deriving energy from such bioenergy projects. In our analysis, cottonwood sequestered the highest amount of carbon in the live roots, dead roots, and surface biomass as residue and switchgrass sequestered the highest amount of carbon as harvestable biomass at the end of the third year. Carbon emission for soybean/grain sorghum rotation was the highest among our three treatments. Cottonwood and switchgrass sequestered 6-times and 3-times more carbon than it emitted during its production, respectively. When sequestration in harvested biomass was considered, ratio of carbon balance was 12 for both bioenergy crops, whereas gross ratio of carbon from the traditional agricultural crop was only 2.2.

Similar to our study on carbon efficiency, energy efficiency can be estimated from such bioenergy projects, i.e., the ratio of energy required for bioenergy production to energy derived from unit land. There were several limitations to our study. We assumed that biomass will be combusted without any further processing except drying which limits the amount of biomass to be co-fired with coal. Although there were both homogeneous and mixed plots for bioenergy crops, we considered all plots for each crop in each site as one unit since detailed record on production activities were not present for both type of plots. Additionally, we did not include any physical or market consequences of such projects since ours is an attributional LCA, as opposed to consequential LCA. Nonetheless, we showed that both cottonwood and switchgrass were more efficient in terms of carbon balance than the control crop rotation of soybean and sorghum. Policymakers should take the carbon benefits into consideration to make informed choices regarding production of bioenergy crops on marginal soils in LMAV.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/9/899/s1, Table S1: Amount of fertilizer applied for production of crops in all three sites, Table S2: Amount of herbicides applied for production of crops in site PTBS, Table S3: Amount of herbicides applied for production of crops in site SREC, Table S4: Amount of herbicides applied for production of crops in site SF, Table S5: Summary of machine horsepower and duration for five major on-site operations in all three sites for the first three years, Table S6: Machine horsepower and duration for planting activities, Table S7: Machine horsepower and duration for fertilizer application, Table S8: Machine horsepower and duration for herbicide application, Table S9: Machine horsepower and duration for harvesting activities.

Author Contributions: Conceptualization, M.H.P. and S.R.M.; methodology, M.F.H.M. and S.R.M.; software, M.F.H.M.; validation, S.R.M. and M.H.P.; formal analysis, M.F.H.M.; investigation, M.F.H.M. and S.R.M.; resources, S.R.M. and H.O.L.; data curation, M.F.H.M., S.R.M., H.O.L. and M.H.P.; writing—original draft preparation, M.F.H.M.; writing—review and editing, M.F.H.M., S.R.M., M.H.P. and H.O.L.; visualization, M.F.H.M.; supervision, S.R.M. and M.H.P.; project administration, M.H.P. and S.R.M.; funding acquisition, H.O.L., M.H.P. and S.R.M. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

C	carbon
CE	carbon equivalent
CO_2e	carbon dioxide equivalent
GHG	greenhouse gases
GWP	global warming potential
ha	hectare
kg	kilogram
km	kilometer
l	liter
LCA	life cycle assessment
NO_X	nitrogen oxides
t	tonne or metric ton

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