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Integrated environmental and economic assessments of producing energy crops with cover crops for simultaneous use as biofuel feedstocks and animal fodder

Kamalakanta Sahoo [a,b,*], Poonam Khatri [c], Akanksha Kanwar [d], Hari P. Singh [d], Sudhagar Mani [e], Richard Bergman [a], Troy Runge [b], Deepak Kumar [f]

[a] Forest Products Laboratory, United States Forest Service, Madison, WI 53726, United States
[b] Biological Systems Engineering, University of Wisconsin–Madison, Madison, WI 53706, United States
[c] Department of Chemical Engineering, Institute of Chemical Technology, Mumbai 400019, India
[d] Agricultural Research Station, Fort Valley State Univ., 1005 State University Drive, Fort Valley, GA 31030, United States
[e] School of Chemical, Materials and Biomedical Engineering, University of Georgia, Athens, GA 30602, United States
[f] Department of Chemical Engineering, State University of New York College of Environmental Science and Forestry, Syracuse, NY, United States

A R T I C L E I N F O

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A B S T R A C T

Energy crops grown on marginal lands offer an alternative supply of renewable resources while avoiding competition with food crops and supporting feed crops. To sustainably grow energy crops, the economic and environmental impacts of various crop management practices such as the adoption of cover crops, fertilization rates, harvesting methods and its end use applications for animal feed or biofuels should be investigated. In this study, we investigated the life cycle analysis (LCA) and economic evaluation of growing two energy crops (energy cane, and napier grass) on the marginal lands with three fertilizer treatments (0, 100, and 200 kg N ha^{-1}), and with a cover crop (clover, *Trifolium incarnatum* L) in the southeastern United States (US). Energy crop was harvested once a year in the late fall for biofuel applications, while the Napier grass was harvested twice a year: first harvested early in spring for animal feed and later harvested in the fall for biofuel application. Experimental field data such as biomass yield, crop management practices, farm inputs, and carbon stored in the soil, were determined to assess the global warming potential and the delivered cost of each energy crop. Napier grass had lower global warming (GW) impacts and biomass delivery costs, 34–153 kg CO_2 eq. per oven-dry metric ton (ODMT) and \$51–\$57 perODMT, respectively than that of energy cane. However, both the energy crops provided carbon sequestrations (−17 and −232 kg CO_2 eq. $ODMT^{-1}$) and thus net GW impact varied between 51 and (−14) kg CO_2 eq. $ODMT^{-1}$ based on the treatments. When the napier grass was harvested for both biofuel and fodder applications, the overall GW impacts and the delivered costs were reduced. Therefore, energy crops can be grown in marginal lands for increased carbon sequestration while reducing the GW impacts of energy crops for biofuel production. The integrated environmental and economic analyzes further demonstrated that the energy crop delivered costs and GW impacts could be further reduced, if the energy crops can be utilized for both biofuel and feed applications.

1. Introduction

The Renewable Fuel Standard (RFS) in the United States (US) requires transportation fuel to contain a definite volume of renewable fuel (Bracmort, 2020). The standard requires an increase in mandated volumes as determined by Environmental Protection Agency (EPA); started with a target of 15 billion liters in 2006 ascending to 136 billion liters target for the year 2022 (Bracmort, 2020). The total renewable fuel requirements are to be met through conventional biofuel (57 billion liters) and advanced biofuels from cellulosic biomass (79 billion liters) (Pennington, 2020). With the increasing demand for advanced biofuels, interest has increased in the cultivation of energy crops on marginal lands. According to the billion-ton report, the US could produce over one billion oven-dry metric tons (ODMT) of biomass annually wherein

* Corresponding author at: Forest Products Laboratory, United States Forest Service, Madison, WI 53726, United States.
E-mail address: kamalakanta.sahoo@usda.gov (K. Sahoo).

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energy crops would account for 411 million ODMT in a baseline scenario, and 736 million ODMT in a high-yield scenario by 2040 (US-DOE, 2016). Although government support has encouraged oil companies to install production capacities, debates on which crop and land types are more suitable for growing energy crops have limited actual production.

Perennial crops such as napier grass (*Pennisetum purpureum*), energy cane (*Saccharum* spp. cv.), miscanthus (*Miscanthus sinensis*), and switchgrass (*Panicum virgatum*) offer advantages such as efficient utilization of light, water, and nitrogen than annual crops (Somerville et al., 2010; Jasinskas et al., 2008). In addition to low input requirements, their high biomass yield potentials and carbon sequestration make them suitable feedstock for advanced biofuel production (Manouchehrinejad et al., 2019; Liang et al., 2018). The selection of crops that can be adapted as energy crops is an important step in the direction to meet sustainable biomass production and supply for bioethanol targets. A sustainable energy crops must fulfill several requirements, such as: (1) easily and reliably transformed in useful forms of energy; (2) high energy density; (3) high spatial density; (4) year-round availability; (5) well-developed agronomic (farming) practices; (6) perennial plant; (7) favorable cost of production and delivery; (8) being amenable to grow under stress conditions and on marginal lands; and (9) highly favorable life cycle balance for both energy and greenhouse gas (GHG) emissions (Matsuoka et al., 2014).

However, growing these energy crops on land that does not induce the food versus fuel debate and supports a viable growth of energy crops remains an important issue. In addition, the impacts of indirect land-use change for biofuel feedstock produced on croplands can increase their net global warming (GW) impact if current land-use is not considered (Emery et al., 2017; Plevin et al., 2010). Consequently, marginal lands which are not suitable to cultivate food crops can be used to grow energy crops (Sahoo et al., 2019; Milbrandt et al., 2014). Biofuels from energy crops would have a much higher net energy output per fossil fuel input compared to that of conventional biofuels (Salassi et al., 2015; Zegada-Lizarazu et al., 2013; Tilman et al., 2006). High net energy outputs are due to: 1) low input requirements because energy crops are perennial, 2) higher bioenergy yield per hectare, and 3) use of all above-ground biomass compared to just seeds in conventional fuels (Tilman et al., 2006). Therefore, using marginal lands to produce energy crops neither competes with food production nor causes biodiversity loss while meeting RFS mandated biofuel targets.

In the US, around 14 million hectares of marginal lands are available for growing energy crops (Emery et al., 2017). These lands cannot support food crops due to economic, climatic, and soil limitations but could significantly increase the supply of biomass needed for biofuel targets (Liu et al., 2011; Bracmort, 2020). These lands have low pH, low organic carbon, and lack sufficient nutrients for crops and are best suited for perennial crops due to strong root systems and are well adapted to poor soils (Feng et al., 2015; Sahoo et al., 2019). Farmers would likely grow perennial energy crops if they can provide an economic return that is at least equivalent or more than other conventional crops (Knápek et al., 2021; US-DOE, 2016). Thus, growing energy crops on marginal lands in the US would make a significant contribution in meeting the biofuel targets without displacing any food crop (Knápek et al., 2021; Mehmood et al., 2017). Some studies have demonstrated the reduced life cycle environmental impacts of perennial energy crops against conventional crops when grown on the marginal lands (Fazio and Monti, 2011; Monti et al., 2009). However, a crop-by-crop quantification of the proposed benefits in reduced environmental impacts and economic costs would be essential on marginal lands.

Considering the characteristics of viable energy crops, energy cane, and napier grass were studied as feedstock for biofuel production. These two perennial crops can have high biomass yields of 15–45 ODMT ha^{-1} yr^{-1} and a carbon sequestration rate of 0.6–3.0 metric-ton (MT) C ha^{-1} yr^{-1} (Robbins et al., 2012; Lemus and Lal, 2005). The biomass yields of different energy crops cultivated on US marginal lands have been reported in the range of 1–27.5 ODMT ha^{-1} yr^{-1} (Mehmood et al., 2017; Stoof et al., 2015). The factors causing this wide range of biomass yields include external irrigation, fertilization, climatic conditions, and species type (Krzyżaniak et al., 2020). Energy cane (*Saccharum* spp. cv. Ho 72–114) is a hybrid developed for the traits of interest like high fiber and biomass yield, and cold tolerance (Knoll et al., 2012; Salassi et al., 2015; Viator and Richard, 2012). As a C4 plant with a high rate of photosynthesis and low rate of respiration has one of the highest dry matter production rates among the known energy crop varieties (Laurent et al., 2015). Energy cane has been used as a potential feedstock for multipurpose uses ranging from the more common burning to generate thermal energy and electricity to a precursor for various forms of liquid fuels (Matsuoka et al., 2014). As productivity is the main driver for the sustainability of any biomass source, energy cane has the potential to effectively contribute to the world's biofuel demands (Monge et al., 2014). Energy cane contains almost double the amount of fiber compared to that of sugarcane. Energy cane bagasse is also used as a combustible energy source, directly or as pellets, in industrial boilers and thermoelectric plants, and as briquettes or pellets in heaters for small industries and households (Manouchehrinejad et al., 2019; Salassi et al., 2015).

Napier grass (*Pennisetum purpureum* Schumach cv. Merkeron) is an herbaceous plant with high cellulosic biomass potential because of its tillering capacity (i.e., production of multiple stems) an important characteristic for the production of bioethanol (Chiluwal et al., 2018). It is commonly known as "elephant grass." Napier grass has a higher biomass yield among other perennial grasses. The ability to propagate readily is another big advantage of napier grass as an energy crop (Lien et al., 2015). Napier grass shows better chemical properties (high cellulose and low lignin), demonstrating its high potential for use as a biofuel feedstock (Mohammed et al., 2019; Rocha et al., 2017). Owing to its fast growth, it can be harvested several times a year, giving high energy output to an energy input ratio of 25:1 (Chiluwal et al., 2019). Another unique characteristic of napier grass is its suitability as a fodder crop for ruminants when harvested at an early stage (Chiluwal et al., 2019). A field study (Chiluwal et al., 2019) in the Southern US showed the second harvesting (harvesting regrowth/ratton crop after six weeks of the first harvest) had good quality (such as high protein content) and could be used as animal fodder by local farmers. It would provide an additional source of revenue for farmers (Chiluwal et al., 2019). A study (Siri Prieto et al., 2017) showed that double-harvest of napier grass produces lower dry matter yield (annual) than single-harvest. But in the longer term, the double-harvest did not have any significant effect on the overall biomass yield (Siri Prieto et al., 2017).

The inclusion of cover crops can sequester and increase both soil organic carbon (SOC) and soil total nitrogen (STN) while helping reduce nitrogen (N) leaching when grown alongside other various crops (Sainju et al., 2015; Jennings, 2010). Field studies have demonstrated that the cover crop treatments combined with bioenergy crops can be used to claim carbon credits, increase N-cycling, improve soil and environmental quality in the regions with similar soil and climatic conditions (Sainju et al., 2015). This study showed that SOC, STN, and nitrate-nitrogen (NO_3-N) increased when energy cane and napiergrass were cultivated with clover cover crop (*Trifolium pretense* L.) and fertilization rates of 0, 100, and 200 kg N ha^{-1} as compared with that of no cover crop (Sainju et al., 2003). Also, the results indicated that clover (an N-fixing legume cover crop) can potentially fix 80–120 kg N ha^{-1} in soil due to symbiotic fixation. Reduced tillage from the cover crop, enhances the residual layer on top of the soil thereby increasing soil fertility due to improvement in nutrient absorption in soil. In addition to N-fixation from legume cover crops, they can control weed growth which could potentially reduce the cost of herbicide applications (Newman et al., 2007). The clover as a cover crop has been reported to increase SOC from 0.1 to 1.0 MT C ha^{-1} yr^{-1} and the STN from 0.03 to 0.11 MT-N ha^{-1} yr^{-1} requiring less N-fertilization and avoiding the associated fertilization costs, thereby improving the economics (Sainju et al., 2017).

Marginal land in the US is available for growing energy crops. Agricultural census data reports 1.15 million hectares of idle or otherwise unused cropland in the US's southeastern region comprises six states, namely Alabama, Arkansas, Florida, Georgia, Louisiana, and Mississippi (USDA-NASS, 2019). Besides, approximately 5.67 million hectares of permanent pasture currently exist in the region (USDA--NASS, 2019). This southeastern region has similar land types and more homogenous crop production systems, allowing for a fair comparison and tabulation of crop production land potential across the entire study region (Salassi et al., 2015). The studies have observed an early planting in August to mid-September produced high fiber yields of energy crops in the southeastern US (Knoll et al., 2013; Knoll and Anderson, 2012). However, the increased interest in growing energy crops on marginal lands demands a sound knowledge of establishment methods and agronomic practices (Jasinskas et al., 2008). Also, it is important to evaluate the cropping systems for different trade-offs against the conventional biomass sources, including the early harvest of biomass for animal fodder use.

The objective of the present study was to quantify the environmental impacts and economic feasibility of producing napier grass and energy cane on marginal lands in the southeastern US considering various scenarios involving fertilization rates, cover crops, and multiple harvests in a year. The novel contributions of the present study are: (1) quantifying the cradle-to-gate environmental impacts and total biomass costs for energy crops on marginal lands; (2) evaluating the application of different fertilization rates and the use of cover crops; (3) evaluating the impact of the double harvest of napier grass and co-producing biofuel feedstock and animal fodder; and (4) a sensitivity analysis on key input parameters impacting the farm-gate cost and the total revenue to the farmers.

2. Material and methods

A cradle-to-gate LCA approach [cradle (i.e., farm) to the plant gate] was followed to quantify the environmental impacts. Although, eleven environmental impacts were estimated only GW impact was presented and discussed here, and other impacts were presented in the supplementary document. A machine rate model (Sahoo et al., 2019; Sahoo and Mani, 2016) was used to estimate the cost of equipment use, farming operations, biomass harvesting and logistics, storage, and biomass delivered to a biomass conversion facility or a biorefinery. This study used primary data such as biomass yield, crop management practices, and nutrient inputs which were compiled from the field experiments conducted at the Fort Valley State University (FVSU), Georgia, US. The field experiments on napier grass and energy cane included three levels of nitrogen fertilizer applications and the inclusion of cover crop with annual harvests. An additional scenario was considered for napier grass of two harvests in a year: the first in mid-October for biofuel feedstock and the second 6-weeks later for fodder. There were no additional nutrient inputs and farming operations except harvesting and logistics of fodder. The experimental details on multiple harvests of napier grass and use of biomass as biofuel feedstock and fodder and the fodder yield data used in this study were obtained from (Chiluwal et al., 2019).

2.1. Life-cycle assessment

The LCA followed the ISO 14040 and 14044 standards (ISO, 2006a, 2006b). The primary goal of the field experiment was to access the biomass yield and its composition with respect to various crop management practices and fertilizer inputs that are used to build life cycle inventory (LCI). The data such as fuel use during the operation of the equipment in crop establishment, cultivation, harvesting, logistics, and transportation were estimated based on ASABE standards (ASABE, 2011, 2006) and published articles on biomass logistics (Khanna et al., 2008; Sahoo and Mani, 2016, 2015). SimaPro 9.1 software was used to build the LCA model and estimate the associated life-cycle impacts, including GW (PRe'Consultants, 2019). Mass and economic allocation approaches were used when needed for attributing LCI flows and impacts among various co-products in the LCA and economic analysis of biomass delivered to the plant.

2.1.1. Goal and scope

The goal of this study was to estimate the lifecycle environmental impacts and economic costs of producing napier grass and energy cane and being delivered to a biorefinery. The scope of the LCA study covered all stages of napier grass and energy cane production and its delivery to a biomass conversion facility. The geographic location for this study was marginal land in the southeast US. The functional unit was 1 ODMT of biomass (as rectangular bale) delivered to the biorefinery. Once napier grass and energy cane are established, they can produce biomass every year consistently for 10–20 years. A 15-year life-cycle was assumed for both crops with crops removed at the end.

2.1.2. System boundaries and biomass supply chain

Fig. 1 shows the system boundary of the energy crop production system. The system boundary covered crop establishment, cultivation, harvesting (i.e., reaping, baling, stacking), storage, and delivery to a biomass conversion facility (Fig. 1). All inputs including fertilizers, chemicals, fuels and lubricants, and equipment were covered in the study. Direct and indirect N_2O emissions were estimated from (i) synthetic nitrogen fertilizer, (ii) nitrogen in the biomass degraded in the soil biomass, (iii) soil emissions during crop removal at the end of the life-cycle. The emissions from synthetic nitrogen fertilizer and nitrogen in the biomass that remained in the soil were estimated using IPCC Tire-II guidelines (Eggleston et al., 2006).

2.1.2.1. Field preparation, crop establishment, and crop removal. In fall 2008, energy cane and napier grass were established in marginal lands at the Agricultural Research Station Farm, FVSU, US (32°55´ N, 83°89´ W). The soil was classified as Dothan sandy loam with a pH of 6.5–6.7 and 0–2% slopes. Both energy crops were harvested consistently from 2011 to 2019. Sainju et al. (2017) provides a detailed description of experimental field preparation and establishment of napier grass and energy cane. Herbicide such as glyphosate was used to get rid of existing vegetations and weeds. The field was prepared for planting with primary and secondary tillage. Lime was added to the field in between tillage operations. The rooted stems or splitting of rhizomes of napier grass and billets of energy cane were planted with a rhizome planter.

The estimated herbicide, fuel, lime, and machine inputs for establishment and cultivation were provided in Tables 1 and 2. This study included the crop removal at the end where the land can be either used to grow energy crops again or food crops. Crop removal included the application of herbicide and deep tillage. In the process of crop removal, fugitive emissions occurring as nitrous oxide (N_2O) and excessive carbon dioxide (CO_2) emissions released due to degradation of soil organic carbon were considered. It was assumed that about 0.34 kg-N_2O and 1500 kg-CO_2 were emitted per hectare of the land in the removal process (Dufossé et al., 2014; Sahoo et al., 2019; Sahoo and Mani, 2019).

2.1.2.2. Cultivation. The cultivation and management of energy crops include only the application of fertilizers based on the treatments which considered various rates of nitrogen-phosphorus-potassium (N-P-K) fertilizer applied to the field and overcrop (Table 1). The nitrogen application rates were 0, 100, and 200 kg N ha^{-1} based on the treatments. However, the application rate of P and K remain the same for the fertilizer treatments (10 kg P ha^{-1} and 10 kg K ha^{-1}). The cropping system also modeled scenarios using clover as a cover crop, with it planted between rows to suppress weeds, retain moisture, and act as a source of nitrogen to the main crop.

2.1.2.3. Harvesting. Table 3 summarizes the average yield data for

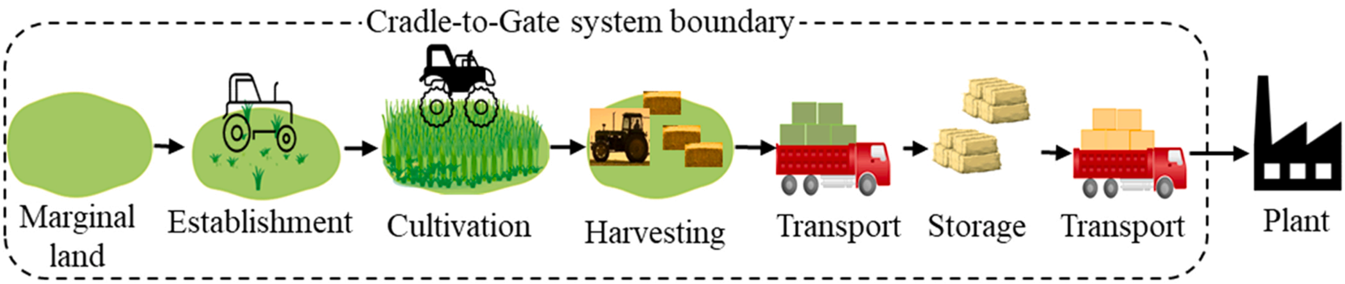


Fig. 1. Cradle-to-gate system boundary of energy crops produced and delivered to the biomass conversion facility.

Table 1
Establishment and cultivation inputs for the energy crop production.

Input materials	Unit	Application rate for napier grass and energy cane	Cost	References
Rhizomes/ billets	Number/ ha	9000	$0.1/Pcs	(Sainju et al., 2017)
Lime	kg/ha	10,000	$0.056/ kg	(USDA-NASS, 2019)
Nitrogen	kg-N/ha	0, 100, 200	$0.42/kg	(USDA-NASS, 2019)
Phosphorous	kg-P/ha	10	$0.46/kg	(USDA-NASS, 2019)
Potash	kg-K/ha	10	$0.44/kg	(USDA-NASS, 2019)
Herbicide(i.e., glyphosate)	kg/ha	3.5	$5.53/kg	(USDA-NASS, 2019)
Cover crop(i.e., clover) seed	kg/ha	25	$3.31/kg	(Sainju et al., 2017)
Fuel and lubricants	L/ha	Table 3	Estimated	(Sahoo and Mani, 2016)

energy cane and napier grass production from the experiment conducted FVSU from 2011 to 2019 with five treatment combinations as scenarios: Scenario 1 (Base scenario): no N fertilizer; Scenario 2: Cover crop only; Scenario 3: Cover crop with 100 kg N ha^{-1} fertilizer; and Scenario 4: 100 kg N ha^{-1} fertilizer only; and Scenario 5: 200 kg N ha^{-1}fertilizer and cover crop.

Harvesting included mowing and conditioning stems, raking, baling, and stacking. This study assumed that both energy cane and napier grass were harvested as large rectangular bales (2.4 m x 2.4 m x 1.2 m). In scenario 3, we assumed that napier grass was harvested early for biofuel feedstock, and later or before the 1st frost, regrowth was harvested as a rectangular bale as fodder to feed animals.

2.1.2.4. Storage. Energy crops are seasonal and thus need to be stored somewhere in the biomass supply chain to fulfill the daily needs of a biorefinery operating throughout the year (Sahoo and Mani, 2017). A commercial-scale biorefinery requires a large volume of biomass in a year which can be stored either at the plant or at intermediate storage locations. Large storage space is required to store all biomass required to fulfill the biorefinery's annual demand and storing them at the plant site can be a costly option and sometimes impractical or infeasible. Thus, it was assumed that the rectangular biomass bales were stored in intermediate storage locations are the mid-way between farms and the biorefinery.

Fugitive GHG emissions such as nitrous oxide, methane, and carbon monoxide during the storage of bales were considered in this study (Emery and Mosier, 2015; Sahoo and Mani, 2019). On average, bales were stored for six months of a year (Sahoo and Mani, 2017). Storage unit operation may include unloading of bales from trucks, stacking, and loading of bales onto trucks. However, we assumed that these activities

Table 2
List of field operations and farm machinery used for cropping cycle of napier grass and energy cane.

Field operation	Equipment	Power[b]	Width[b]	Speed[a]	Field capacity[a]	Equipment's life[a]	List Price[b]	Fuel
Units		kW	m	Km/h	Ha/h	Years	$	l/ha
Establishment and crop removal								
Spraying chemicals	Self-propelled sprayer	123	24.40	11.0	17.4	12.0	269,218	1.81
Primary tillage	Moldboard plow		3.20	7.0	1.9	10.0	22,037	
	Tractor	183		7.0	1.9	12.0	238,501	24.65
Secondary tillage	Disc plow		9.34	10.0	7.5	10.0	67,776	
	Tractor	239		10.0	7.5	12.0	364,435	8.20
Planting cultured material	Planter for stem		3.00	9.0	1.8	10.0	33,000	
	Tractor	86		9.0	1.8	12.0	63,600	12.56
Cover crop seeding	Planter (No-Till)		9.60	11.0	9.0	10.0	144,429	
	Tractor	116		11.0	9.0	12.0	174,296	3.31
Cultivation								
Fertilizer application	Fertilizer applicator		27.40	11.0	21.1	10.0	112,000	
	Tractor	239		11.0	21.1	12.0	324,077	2.91
Spraying chemicals	Self-propelled sprayer	123	24.40	11.0	17.4	12.0	269,218	1.81
Harvesting								
Mowing and conditioning	Mower		4.90	8.0	3.1	10.0	50,664	
	Tractor	112		8.0	3.1	12.0	147,490	9.17
Raking	Wheel Rake		8.80	10.0	7.0	10.0	39,277	
	Tractor	82		10.0	7.0	12.0	123,149	2.99
Baling	Large square baler			8.0	3.1	10.0	156,499	
	Tractor	145		8.0	3.1	12.0	170,464	11.91
Stacking square bale	Bale stack maker		3.00	16.4	1.6	10.0	62,000	
	Tractor	112		16.4	1.6	12.0	140,711	17.83
Loading/unloading bales	Front-end loader					12.0	20,875	
	Tractor	127		–	5.1	12.0	161,376	6.38

[a](ASABE, 2011); [b](DEERE, 2019)

Table 3
Summarized scenarios for energy cane napier grass production (FVSU experiment 2011–2019).

Scenarios	Scenario description	Biomass yield	
		Average (ODMT/ha)	Standard deviation
Scenario 1	Napier grass	21.50	9.54
(base case)	Energy cane	12.49	5.81
Scenario 2	Napier grass + Cover crop	23.17	10.21
	Energy cane + Cover crop	10.35	5.79
Scenario 3	Napier grass + Cover crop + 100 kg-N/ha (Double harvest)	22.19 1.10[a]	13.12 0.20
	Energy cane + Cover crop + 100 kg-N/ha	12.50	6.78
Scenario 4	Napier grass + 200 kg-N/ha	21.15	12.52
	Energy cane + 200 kg-N/ha	12.70	7.06
Scenario 5	Napier grass + Cover crop + 200 kg-N/ha	23.73	10.43
	Energy cane + Cover crop + 200 kg-N/ha	15.81	9.07

[a]Chiluwal et al. (2019)

were part of transportation activity.

2.1.2.5. Transportation. It was assumed the bales were transported in trucks (i.e., a tractor with a flatbed trailer), and each trailer carried about 36 large rectangular bales (Sahoo, 2017). Initially, all bales were transported to intermediate storage locations, and later bales are moved from storage to the plant based on the daily biomass demand of the biorefinery. Overall, each bale was transported 50 km (1-way) which is the distance between farms and the biorefinery. Bales were loaded and unloaded from the truck twice, one time between farm to storage and the second time from storage to biorefinery. This study considered the fuel and machine used during loading and unloading of bales as well as transportation of the bales.

2.1.3. Life-cycle inventory (LCI)

The LCI flows were estimated with data from the crop production's lifecycle. The unit process inventories were estimated with mass and energy balance analysis of each crop using the primary field data and the secondary data from published literature. The LCI analysis includes all material and energy inputs to each stage or a unit operation of the biomass supply chain. Fuel and machine use per unit of biomass output was estimated considering the field capacity (Table 2) and biomass yield at the farm gate (Table 3). Mass loss of about 20% during harvesting, 4% in logistics and transportation, and 7% in storage were considered in the analysis.

2.1.4. Life-cycle impact assessment

The life cycle impact assessment (LCIA) phase establishes associations between the LCI results and potential environmental impacts using a certain impact assessment method. This study used the TRACI (Tools for the Reduction and Assessment of Chemical and other Environmental Impacts) impact assessment method (Bare, 2010; Bare et al., 2000) to estimate the target impact indicators. However, only the GW impact category was presented in this study. The results were shown as total greenhouse gas emissions from field to delivery of energy crops to the biorefinery. Although this is a cradle-to-gate LCA study, we also provided the results on carbon stored in the soil or carbon sequestration by energy crops on the marginal lands. LCA results for impact categories other than GW are provided in the Supporting information.

In the long term, perineal energy crops sequester carbon in the soil (Krzyżaniak et al., 2016, 2020; Sainju et al., 2017) and thus may help in mitigating climate change. Although the scope of this study was the cradle-to-gate, the results on carbon sequestration by napier grass and energy cane were estimated based on a study from the same experimental plots (Sainju at al, 2017). The supporting document (Table A1) provided the annual carbon sequestration values by napiergrass and energy cane.

2.2. *Economic analysis*

The cost of biomass delivered to the biorefinery included the cost of materials inputs and machine inputs and the total cost of biomass delivery to a biorefinery was expressed on an ODMT basis. The projected cost estimation included all the field operations from crop establishment and cultivation, harvesting and aggregation (baling), storage, transportation, and finally crop removal. Material inputs are one-time activity during the establishment period and at the end during crop removal and annual cultivation inputs include fertilizers and chemicals. Except for establishment and crop removal, machine inputs are annual. Due to the lower productivity of marginal land, annual rent is lower than cropland with average cash rent of $25 per hectare which was included in the cost estimation of biomass (USDA-NASS, 2019). The details of material inputs and corresponding prices are listed in Table 2.

The machine rate model was used to estimate the hourly cost of operating each piece of equipment (Sahoo, 2017; Sahoo et al., 2019; Sahoo and Mani, 2016). Except, self-propelled equipment, generally a farm operation includes an implement and a recommended tractor to operate the implement. Based on the literature and ASABE Standard D497.7 (,(ASABE, 2011), a set of equipment and tractor were considered in this study to estimate the cost of each unit operation. Cost estimates for farm machinery operations and performance parameters were calculated using ASABE standards, EP496.3, and D497.7 (ASABE, 2011, 2006). List prices for farm machinery were estimated using John Deere Build Your Own web tool (https://configure.DEERE.com) (DEERE, 2019).

2.3. *Sensitivity analysis*

A sensitivity analysis was conducted to understand the farm economics and to evaluate the influence of critical input parameters on the farm-gate price of the dry biomass for both crops. The key parameters included fertilizer cost, total fuel cost, biomass yields, and land cost. Sensitivity analysis for each parameter was estimated by changing only one parameter at a time from the base case while assuming that these inputs are mutually exclusive.

3. Results and discussion

Although this work estimated various cradle-to-gate environmental impacts (Table A2 and A3), only GW impacts and cost of biomass delivered to a biorefinery were presented and discussed in the following results sections.

3.1. *Biomass yields on marginal land*

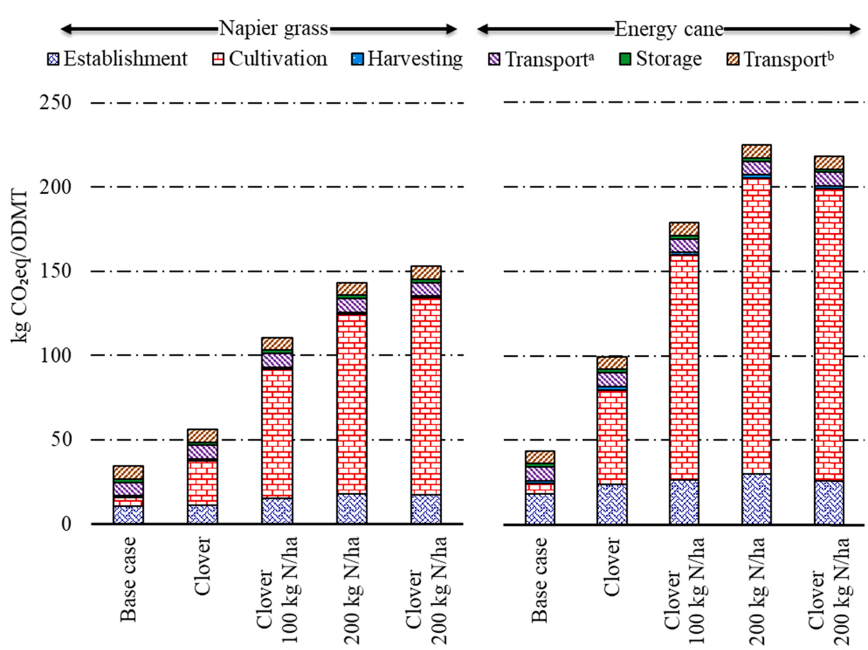
The field experiments data (2011–2017) on cultivation of napier grass and energy cane on marginal lands showed average biomass of 22.4 ODMT $ha^{-1}yr^{-1}$ and 12.8 ODMT $ha^{-1}yr^{-1}$, respectively. Though both crops were grown without additional irrigation, various factors like incorporating cover crop and nitrogen fertilization influenced the dry biomass yields. However, the impacts of various treatment, especially use addition of various rates of fertilizers on the annual biomass yield were not statistically significant. The biomass yields of napier grass and energy cane varies between 16 and 24 and 10–16 ODMT $ha^{-1}yr^{-1}$ among five treatments, respectively (Table 3). The detailed analysis of biomass yield for the same experimental plots from 2011 and 2014 was presented by Sainju et al. (2017). Lee et al. (2018) summarized the experimental biomass yield of energy cane from various southern states in the US which varied between 12 and 44 ODMT $ha^{-1}yr^{-1}$. Knoll et al. (2021) mentioned the biomass yield of five variety of energy cane (14–20 and

24–32 ODMT ha^{-1}yr^{-1}) and the biomass yield varied between two locations significantly due to variations in climate and weather conditions. Other research works on marginal lands in the U.S. have reported the biomass yield up to 17.4 ODMT ha^{-1}yr^{-1} for switchgrass (Stoof et al., 2015). Similar research works on marginal lands in Europe reported biomass yields of 29.8 ODMT ha^{-1}yr^{-1} for Miscanthus, 10.71 ODMT ha^{-1}yr^{-1} for willow, and 9.68 ODMT ha^{-1}yr^{-1} for poplar (Olba-Zięty et al., 2021). Usually, perineal crop's biomass yield from marginal land were lower than fertile cropland (Sahoo et al., 2019) and the biomass yield used in this study (marginal land) were lower than the biomass yield from usual cropland (Knoll et al., 2015; Knoll et al., 2021). The experimental plots used in this study did not find any differences in the performance of agricultural implements while used in marginal land compared to that of cropland. Furthermore, the benefits of incorporating short duration cover crop with energy crops would also encourage the farmers to pursue the marginal land cultivation. Overall, these results indicated a significant potential in growing energy crops on the marginal lands which are not ideal for conventional crop cultivation.

3.2. Global warming impacts of energy crops

The cradle-to-gate global warming (GW) impacts of two energy crops are presented in Fig. 2. The total GW impacts per functional unit (i.e., ODMT of biomass delivered to a biorefinery) ranged from 34 to 153 kg CO_2 eq. and 44–225 kg CO_2 eq. for napier grass and energy cane, respectively. In this study, the main contributing processes for GW impacts of energy cane system were cultivation, establishment, and transportation. The GW impacts of the cultivation stage increased from scenarios 1–5 because of applications of fertilizer and the use of cover crops. In the case of napier grass, the cultivation stages contributed up to 77% of the GW impacts. This share of the cultivation stage increased from scenarios 1–5, mainly due to the increased amount of fertilizer. The fertilizer-based N_2O emissions (direct and indirect) contributed 64% to the GW impacts of the cultivation stage. In the establishment stage of napier grass, the impacts of scenario 1 (with 0 kg N ha^{-1}) were the largest (31%) owing to low yields and various applied field treatments and soil preparation activities. The cultivation and establishment stages collectively accounted for 45% of the GW impacts in scenario 1 with no fertilizers and cover crop. In scenario 2, where the cover crop was cultivated with no fertilizers, an increase in biomass yield was accompanied by a 64% increase in the GW impacts with a maximum increase in impacts of the cultivation stage (from 4.9 to 26.7 kg CO_2 eq. ODMT $^{-1}$). The largest contributing emissions to total GW impacts were N_2O (86%). In scenarios 3, 4, and 5, the addition of fertilizer with and without cover crop did not seem to affect the biomass yield. However, the GW impacts were increased significantly due to the use of N-fertilizer on the field. The reason for low biomass yield in energy crops treated with fertilizer (100 kg N ha^{-1}) could not be explained (Sainju et al., 2017, 2015, 2003). The cradle-to-farmgate GW impacts (similar to scenario 3) of napier grass estimated in this study (~90 kg CO_2 eq. ODMT $^{-1}$) was much higher than to a recent study (Somjai and Suwan, 2020) in Thailand. This was due to assumptions of a very high biomass yield (~110 tonnes ha^{-1}) of napier grass in the latter case compared this study (22.2 ODMT ha^{-1}). Liu et al. (2017) estimated the cradle-to-plant gate GW impacts (41 kg CO_2 eq. ODMT $^{-1}$) of miscanthus produced in the northeastern US and having similar biomass yield compared to this study. The differences in GW impacts between these studies can be attributed to the crop management practices and biomass yield. Krzyżaniak et al. (2020) estimated the GW impacts of giant miscanthus delivered to a plant for the geographic region such as Poland. The cradle-to-plant gate GW impact was estimated to be 33.8 kg CO_2 eq. ODMT $^{-1}$ and this value was within the range of GW impacts (34 – 152 kg CO_2 eq. ODMT $^{-1}$) estimated in this study. The lower GW impacts in the former study can be attributed to the very high yield of miscanthus compared to biomass yield of napier grass considered in this study and the use of digestate as the substitute for the mineral fertilizers.

For all energy cane scenarios, the total GW impacts were higher than the napier grass. This could be explained by the lower biomass yields in energy cane compared to napier grass. The contributions of cultivation, establishment, and transport stages varied from 14% to 80%, 12–41%, and 7–36%, respectively. There was an average 77% increase in GW impacts in the establishment of energy cane compared to those of napier



[a]Biomass transported from field to intermediate storage locations; [b]Biomass transported from intermediate storage locations to a biorefinery

Fig. 2. Cradle-to-gate life cycle global warming (GW) impacts of napier grass and energy cane [a]Biomass transported from field to intermediate storage locations; [b]Biomass transported from intermediate storage locations to a biorefinery.

grass. This increase was 64% for the cultivation stage; however, the contributing emissions followed the same trend in both crops. Among all scenarios, the largest increase in GW impacts was observed in scenario 2 with cover crop and no fertilizer use when comparing both. In other scenarios, the use of fertilizers largely contributed to the lesser difference in GW impacts of the two crops. This supports the need for more studies on energy crops to understand the influence of cover crops and fertilizer rates also described by Sainju et al. (2017). Energy crops sequester carbon below-ground and the influence of carbon sequestration on net GW impacts is presented in Fig. 3.

For scenario 1, carbon sequestration by napier grass and energy cane crops decreased their net GW impact by 50% and 67%, respectively in the 1st scenario. As evident from Fig. 3, the scenarios of energy crops with clover and fertilization were able to sequester more carbon per functional unit. Energy cane showed larger carbon sequestration in all scenarios mainly due to the influence of below-ground biomass of the crops. These findings were in agreement with opinions by other research studies (Sainju et al., 2003, 2017, 2015). There are several studies on LCA of different energy crops (Mehmood et al., 2017; Krzyżaniak et al., 2018). The GW impacts of base case scenario (without fertilization) were similar to those reported for the production of giant miscanthus (33.8 kg CO_2 eq per ODMT) on marginal soils (Krzyżaniak et al., 2020).

3.3. Economic analysis

Fig. 4 presents the total costs involved in cradle-to-gate delivery of napier grass and energy cane to a biorefinery as well as the contribution of various operations from crop establishment to biomass delivered to the plant. The plant gate costs for napiergrass (established and cultivated on marginal lands) delivered to a biorefinery located 50 km away from the field was varied from \$50-\$57 ODMT^{-1} .

Biomass harvesting (30–33%), storage (12–13%), and transportation (32–36%) were the major contributors to the total plant gate cost. The plant gate cost of napier grass was the lowest from scenario 2 (cover crop) and the highest from scenario 4 (200 kg N ha^{-1}) due to reduced biomass yield. The plant gate cost of energy cane varied between \$61-\$68 ODMT^{-1} . The contributions of different unit costs towards plant gate cost of energy cane were like napier grass. Irrespective of crop type and treatments, the biomass production (i.e., rent, establishment, and maintenance) and its logistics (harvesting, storage, and transport contributed 20–30% and 70–80% of biomass's plant gate cost, respectively. In contrast to environmental impact results, the contribution of biomass logistics towards total cost was much larger and significant than crop establishment and cultivation.

Overall, the total delivery cost of napier grass was about 14% (10–18%) lower than that of energy cane due to higher biomass yield.

A comparison of cost estimates for each field operation indicated that the cultivation and harvesting operations contributed the most to the total costs of production for both crops. The harvesting operations had the highest cost inputs primarily due to their labor-intensive nature of the operation (Mathanker et al., 2015). The second-largest cost contribution was from transportation (14 –17%) of the baled energy crops to a storage facility and from a storage facility to the plant gate. Overall, the results of environmental and economic assessments were found to be in agreement.

Compared to the present study, the biomass cost of napier grass and energy cane delivered to a power plant were estimated to be about \$37 and \$31 ODMT^{-1} respectively by Masum et al. (2020). The lower biomass cost estimated by Masum et al. (2020) were due to differences in many inputs including very high biomass yield (e.g., biomass yield of energy cane was assumed to be twice compared to present study). But Salassi et al. (2014, 2015) estimated the energy cane production cost

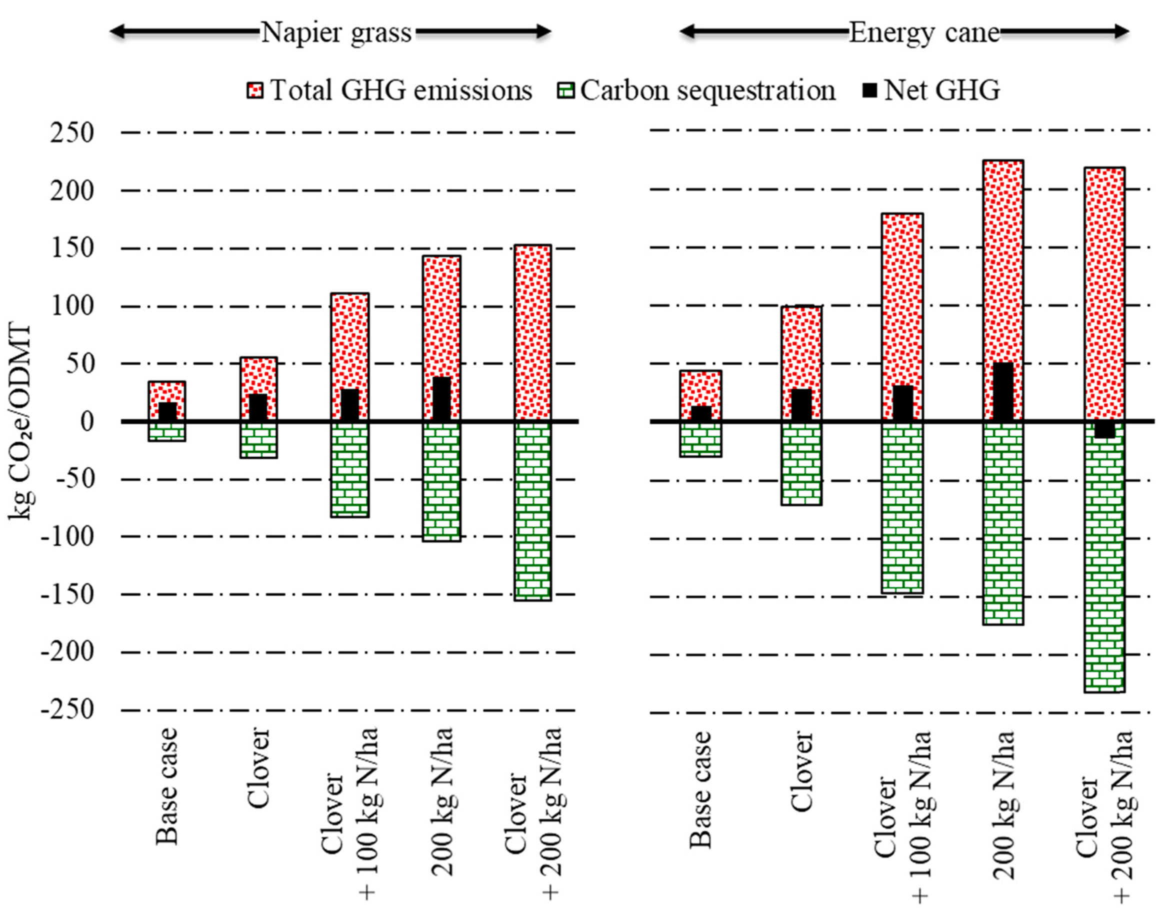
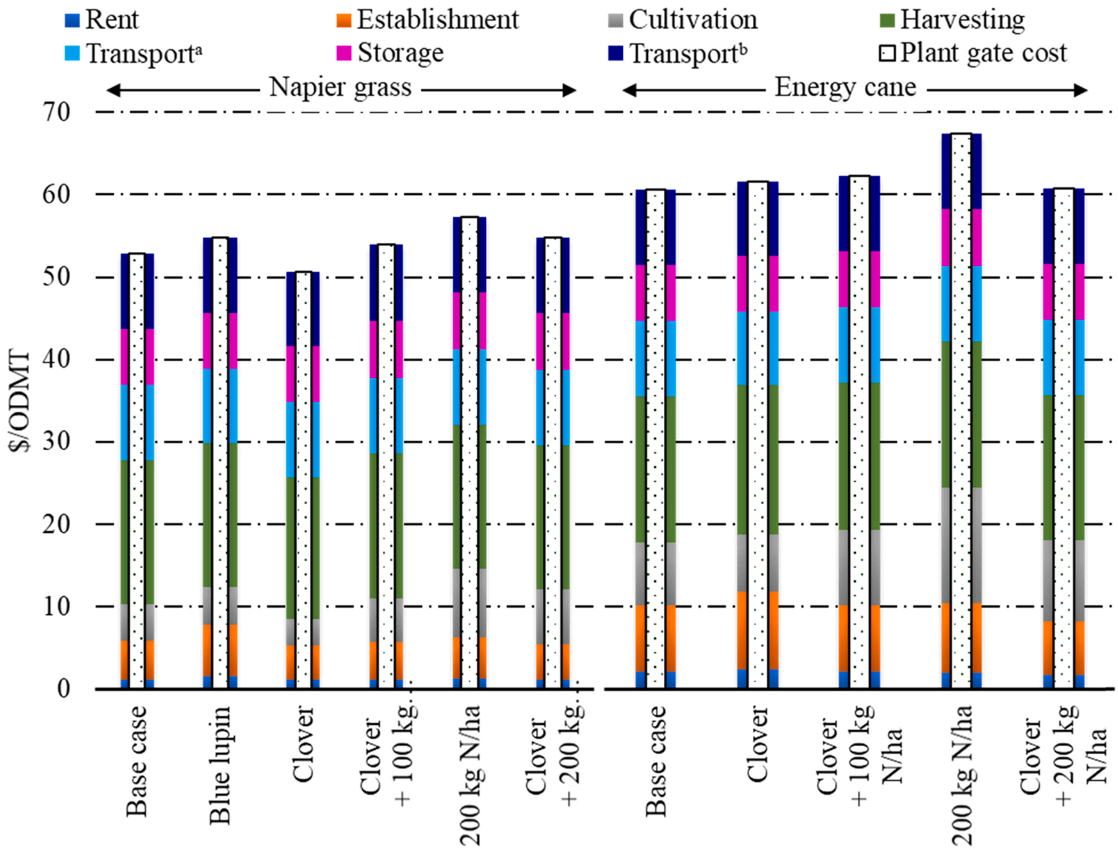


Fig. 3. Net global warming impacts of energy crops considering carbon sequestration.



[a]Biomass transported from field to intermediate storage locations; [b]Biomass transported from intermediate storage locations to a biorefinery

Fig. 4. Comparison of costs of production of napier grass and energy cane on the marginal land in different scenarios.

that varies between \$105-\$127 $ODMT^{-1}$ which was much higher than the present study. The higher biomass cost can be attributed to differences in the crop management practices, biomass yield, life of the crop and calculation method. However, the biomass cost delivered to a biorefinery estimated in the present study were within the values (\$45-\$110 $ODMT^{-1}$) as estimated by the 2016-billion-ton report (US-DOE, 2016).

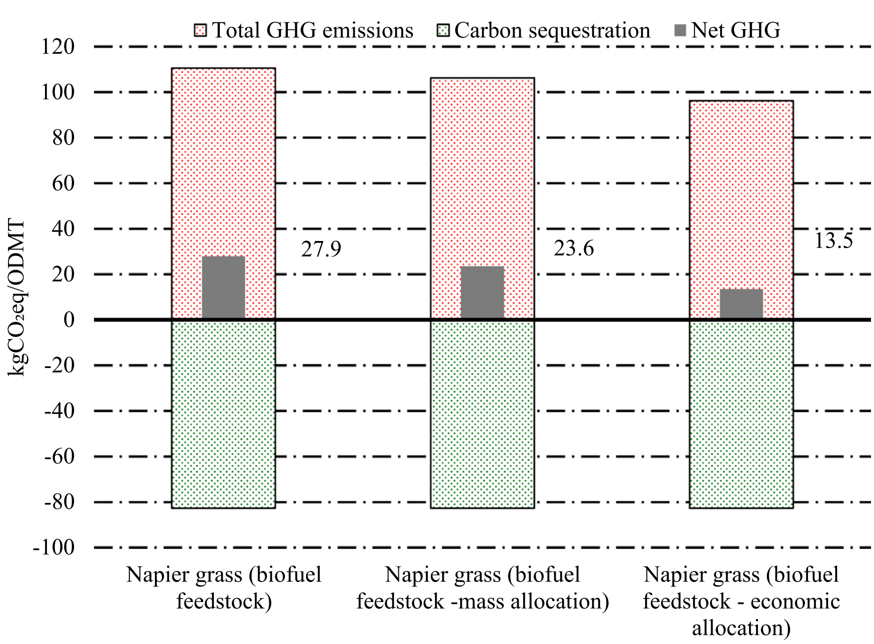


Fig. 5. Cradle-to-gate GW impacts of napier grass with different harvesting schemes and allocation choices along with carbon sequestration.

3.4. Impact of multiple harvests of napier grass for biofuel feedstock and fodder use

In scenario 3, where napier grass was cultivated with cover crop and 100 kg N ha^{-1} , a second harvest was done at an interval of six weeks after the first harvest. This second harvest was used as animal fodder. Fig. 5 and Fig. 6 show the influence of double harvest (early harvest used as biofuel feedstocks and second harvest used as animal feed) on overall GW impact and total plant delivered cost of napier grass, respectively. The cradle-to-gate GW impact of napier grass biomass delivered to plant was reduced by 4 – 13% compared with single harvest scenario. These reductions were quantified based on the type of allocation considered in the LCA study. Due to the price differences between the biomass for biofuel use and animal feed use, the allocation factors for the partitioning of impacts from two napier grass harvests were estimated to be 0.95 and 0.84 for mass and economic values, respectively.

Fig. 6 shows the reduction in the total cost of biofuel feedstocks when considering the credits (i.e., net profit from selling napier grass for animal feed) from the second harvest of napier grass as animal feed. The delivered cost of the feed was estimated to be \$152 $ODMT^{-1}$. Fodder crop logistics and transportation cost was about \$25 $ODMT^{-1}$. Farmers can sell fodder biomass at the market price of \$221 $ODMT^{-1}$ or \$165 MT^{-1} (USDA-NASS, 2019), while selling fall harvested biomass for biofuel production. If profits from selling fodder were considered as credit towards the cost of biofuel feedstocks, the estimated biomass delivered cost was reduced by 7% from the base cost of \$54 to \$50 $ODMT^{-1}$. The result has demonstrated that the double harvesting of napier grass, especially producing biofuel feedstocks and fodder, can be a better option for reducing environmental impacts and costs of napier grass. The dual purpose of napier grass can be very attractive to farmers holding marginal lands to help offsetting the supply and demand risks. In addition, the farmers have a flexibility to produce napier grass on-demand for animal feed or for biofuels in a particular year with storage options.

3.5. Variations in global warming impacts and cost of biomass

Fig. 7 shows the results for a set of sensitivity parameters influencing the biomass delivery cost and net GHG emissions obtained by changing various input and output parameters from a base value. With 20% increase or decrease in biomass yield could impact the delivery costs per metric ton of the biomass by 5%. The biomass delivery costs were found most sensitive to change in equipment cost (~8%). The rest of the parameters did not influence the biomass delivery costs by more than 5%. The highest impact on net GHG levels was made by carbon sequestration levels. With a 20% decrease in carbon sequestration, net GHG impacts increased by 60%. The next high impacting variable was fertilizers application rate which showed around 40% change in GHG emissions due to relative increase or decrease in the field emissions. Another fertilizer-related parameter with a noticeable influence on GHG emissions was the choice of emission factors for nitrous oxide. A 20% change in biomass yields would make a two-fold impact on the environmental impacts. Furthermore, a change in the life of energy crops was also impacting the net GHG levels by about 30%. Although carbon sequestration rate did not influence the biomass delivery costs (~8%), a large effect was noticed on the environmental impacts (~60%). Therefore, if the carbon credits can be proposed for energy crops with increased carbon sequestration rate, a further reduction in the cost of energy crops can be highly attractive to biofuel production. Future studies should focus on developing carbon credit strategies for growing energy crops while reducing economic risks to farmers. In addition, the role of cover crops should be investigated to evaluate its long-term potential to reduce the use of chemical fertilizers while producing low-cost and less carbon intensive energy crops that supports both a biorefinery and an animal feed sector.

4. Conclusions

Increased attention has been paid to growing cellulosic biomass crops to meet the renewable fuel targets in the U.S. Marginal lands can be the attractive for growing energy crops without competing for food crops while supporting animal feed industries. Field experimental data including the biomass yield, carbon sequestration rate and various agronomic management practices such as fertilization rate and cover crops were used to evaluate the economic and environmental impacts of producing energy cane and napier grass for biofuel applications. The cradle to gate GW impact of napier grass was much lower than that of energy cane due to higher biomass yield. For both crops, GW impacts increased with increase in fertilizer application rates due to low or marginal increase in biomass yield. However, the use of cover crops with energy crop production showed lower GW impacts of biomass delivered to biorefineries. Furthermore, considering the carbon sequestrations in soil by energy crops, the net GW impacts were reduced substantially (in some cases, even negative) based on the treatments. For all scenarios,

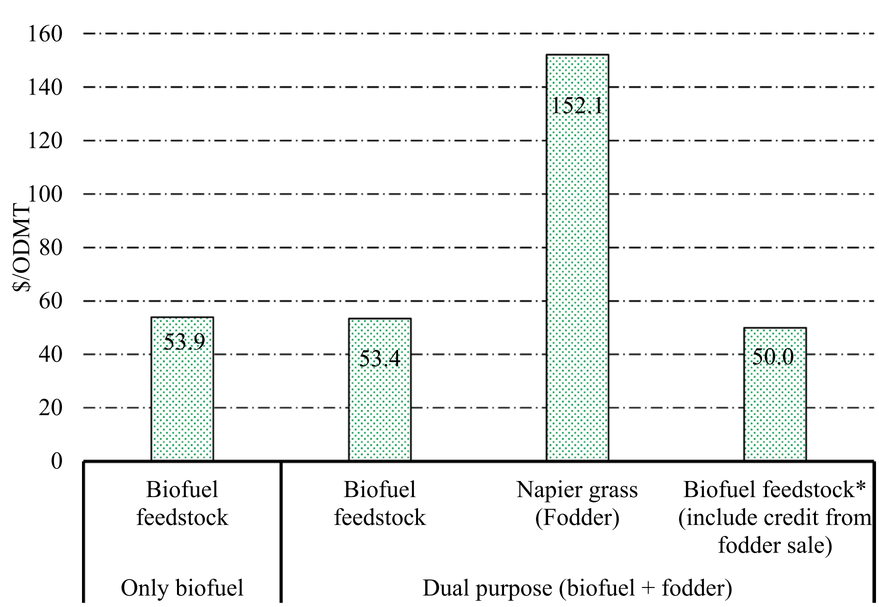


Fig. 6. The impact of double harvest on the plant delivered cost of biofuel feedstocks.

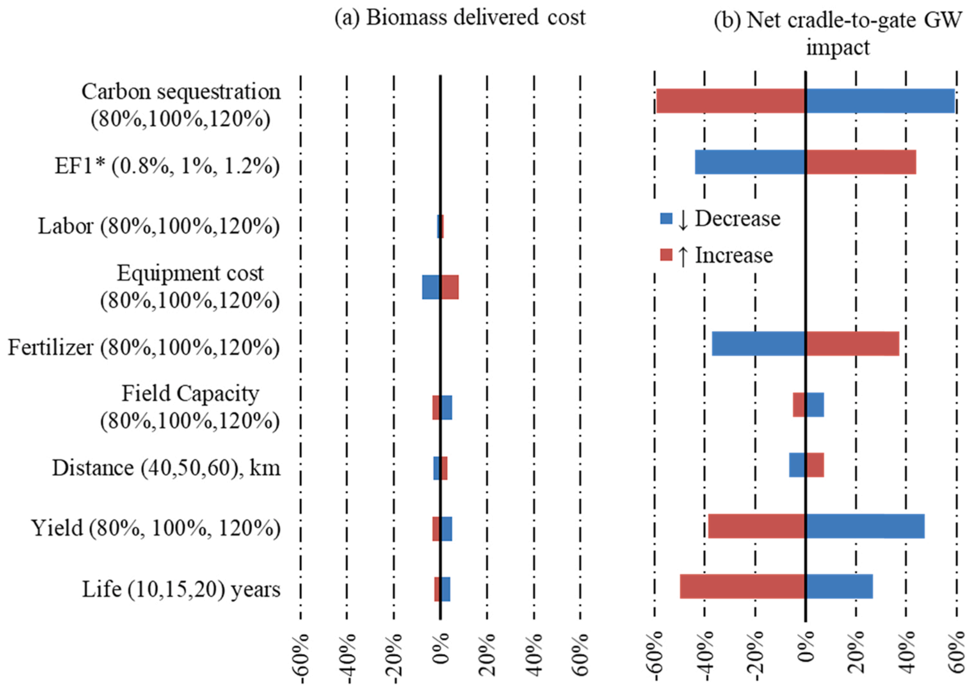


Fig. 7. Variations in the results [(a) plant delivered cost, (b) Net cradle-to-plant gate GW impact] of napier grass (clover + 100 kg N ha^{-1}) delivered to a plant due to a 20% increase and 20% decrease in the critical inputs (*Emission factor for N_2O emissions per kg-N input).

energy cane showed larger carbon sequestration rate mainly due to the higher below-ground biomass yield that contributes more carbon to the soil.

Our estimates demonstrated that the delivered cost of both energy crops grown on marginal lands was up to 30% lower than that of the U.S. Department of Energy's recommended price (~$80 ODMT^{-1}) for biomass feedstocks for biofuels. In addition, the use of cover crops with energy crop production showed a lower biomass delivered cost. The delivered cost of napier grass was lower than that of energy cane due to relative increase in biomass yield. A further reduction in the delivered cost of napier grass can be possible, when the napier grass can be double harvested (the first harvest in Fall for biofuels and the second harvest in Winter for fodder) for both biofuel and animal feed applications. The dual-purpose nature of napier grass can be more attractive and flexible to farmers for help supporting both the biofuel and animal feed industries. Overall, the integrated environmental and economic assessments of energy crops grown on marginal lands not only estimated the delivered cost and the net GW impacts of energy crops for biofuel and animal feed applications, but also encouraged to estimate the future carbon credits for growing energy crops on marginal lands in the southeastern U.S.

CRediT authorship contribution statement

Kamalakanta Sahoo: Conceptualization, Methodology, Modeling, Formal analysis, Investigation, Writing – original draft. **Poonam Khatri:** Data curation, Visualization, Writing – review & editing. **Akanksha Kanwar:** Writing – original draft. **Hari P. Singh:** Supervision, Project administration, Funding acquisition, Writing – review & editing. **Sudhagar Mani:** Supervision, Project administration, Funding acquisition, Writing – review & editing. **Richard Bergman:** Project administration, Funding acquisition, Writing – review & editing. **Troy Runge:** Formal analysis, Visualization, Writing – review & editing. **Deepak Kumar:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2022.114681.

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