Life cycle assessment of ethanol production from tropical banagrass (Pennisetum purpureum) using green and dry processing technologies in Hawaii

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This study conducted well-to-pump and well-to wheel life-cycle assessment of fossil energy use and greenhouse gas (GHG) emissions during ethanol production from tropical Banagrass (*Pennisetum purpureum*) using green-processing (with the use of fresh feedstocks) and dry or conventional processing (with the use of dried feedstocks) in the state of Hawaii. 10 000 MJ of energy was used as a functional unit with a systematic boundary drawn based on relative mass, energy, and economic value method using a 1% cutoff value, and the results were compared to those of conventional gasoline, and ethanol from corn and other ethanol lignocellulosic feedstocks. Detailed techno-economic model was built using the SuperPro designer. Ethanol yields were estimated at 0.27 l/kg (green processing with fungal co-product), 0.27 l/kg (green processing without co-product), and 0.29 l/kg (dry-processing) of feedstock, respectively. The well-to-pump analysis indicate that ethanol production consume 8200 MJ (green processing with co-product), 7600 MJ (green-processing without co-product) and 7200 MJ (dry-processing without co-product) of fossil energy and emit approximately144 kg CO_2-eq., 90.6 kg CO_2-eq., and 59.1 kg CO_2-eq. per 10 000 MJ of ethanol produced, respectively; well-to-wheel analysis showed that 280 g of gCO_2-eq., 260 g CO_2-eq., and 250 g CO_2-eq. of emissions were produced per kilometer by driving Flex Fuel Vehicle. In summary, ethanol produced using the green-processing technology required greater amount of fossil energy and produced more GHG emissions compared to that of dry processing technology, due to additional energy needed for fungal growth and related processes. Process power, enzyme, and chemical production during ethanol processing were identified as emissions hot-spots for both green and dry processing. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4893673]

I. INTRODUCTION

A rapid rise in oil prices and an increased awareness concerning anthropogenic climate change have led to concerted efforts to curtail fossil fuel consumption through the use of alternative energy including biofuels. While the world's bioethanol production almost quadrupled over the past decade; the use of food crops for biofuel production—primarily corn in the United States, sugar in Brazil, and oil palm in Southeast Asia, has raised concerns over the food versus fuel debate (REN21, 2010). Against this backdrop, lignocellulosic biofuels have captured growing

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attention as a more sustainable alternative to conventional biofuels (McMillan, 1997; Zaldivar *et al.*, 2001; Cardona and Sanchez, 2007; Laser *et al.*, 2009; Gnansounou, 2010; and Klein-Marcuschamer *et al.*, 2010). Lignocellulosic biomass is abundant and readily available (IEA, 2011 and Slade *et al.*, 2011), and dedicated energy crops such as switchgrass and miscanthus can be grown in marginal environments, reducing direct land use competition. It is also argued that the use of lignocellulosic biomass for fuel production brings a plethora of benefits including soil erosion mitigation, carbon sequestration, and local water quality and wild habitat improvements (Sims *et al.*, 2008 and Tilman *et al.*, 2009), although the long-term sustainability of these options is still debated (Smith *et al.*, 2013 and Ridley *et al.*, 2013).

In the context of Hawaii, a perennial fodder crop known as Banagrass (*Pennisetum purpureum*) has been identified as a promising biomass source due to its robust growth (Black and Veatch, 2010 and Tran *et al.*, 2011) and high carbohydrate content (approximately 37% cellulose and 33% hemicellulose (Takara, 2012)). As Hawaii is highly dependent on imported oil (over 85% of primary energy demand is met through the use of imported petroleum products (DBEDT, 2011), and serves as a military hub in the Pacific region, the use of tropical fodder crops for biofuel production in recent years has been perceived to be of local and regional importance. Furthermore, the novel processing option known as "green-processing," which directly converts freshly harvested biomass into biofuels, has been identified to offer benefits under tropical climates: the green-processing of banagrass eliminates the front-end operation of biomass drying and storage, which can pose an operational challenge due to frequent rain and humidity. The green-processing technology enables the harvesting of plant juice that can be used to produce a high value protein-rich co-product for local fish/animal production (Takara and Khanal, 2011). The feasibility of this processing option has been demonstrated in laboratory scale studies (Takara, 2012); however, a detailed life-cycle assessment (LCA) has not been conducted. Therefore, this study seeks to fill this knowledge gap by providing a life-cycle assessment of this advanced biofuels production option.

Existing literature suggests wide-ranging estimates of energy use and environmental impacts related to the production of biofuels, which demonstrates the complexity and inherent challenge of such LCA studies. Choice of system boundary, feedstock options, conversion technologies and efficiencies, co-product allocation methods are some of the major factors responsible for variation in the LCA results of biofuel production (Gnansounou *et al.*, 2008; Cherubini *et al.*, 2009; and Singh *et al.*, 2010). A thorough review of LCA studies on biofuel production conducted by Borrion *et al.* (2012) concluded that fossil energy use and greenhouse gas (GHG) emissions during production of bioethanol are 56% to 100% and 46% to 90% less than that of conventional gasoline. In terms of emissions sources, the existing studies disagree as to the contribution of each production process: Nitrogen fertilizer emissions are reported to contribute the most, according to Wang *et al.* (2011), while Gonzalez-Garcia *et al.* (2012) reported that ethanol conversion contributes to almost all of the life-cycle emissions. MacLean and Spatari (2009) and Kumar and Murthy (2012) emphasize the contribution of enzyme production in overall life-cycle emissions for cellulosic ethanol. The perceived difference in the footprint of each production process is attributable to the heterogeneity in environmental and technological assumptions. For example, the relative importance of nitrous oxide, which has 298 times more potent global warming potential (GREET, 2012), depends on agro-environmental, technological, and management factors including soil moisture, the rate of fertilizer application, the use of irrigation, and the choice of annual versus perennial crops (Cherubini and Stromman, 2011), and whether the plant becomes a net producer or consumer of electricity also affects overall energy and greenhouse gas footprints.

In terms of geography and feedstocks, the existing literature draws largely on European and North American cases, investigating key biomass options including agricultural waste such as corn and wheat straws, forest residues, and dedicated energy crops including switchgrass and miscanthus (Cherubini *et al.*, 2009 and Borrion *et al.*, 2012). There has been a gradual increase in the number of LCA studies conducted in other regions around the world in recent years (Macedo *et al.*, 2008; Silalertruksa and Gheewala, 2009; and Amores *et al.*, 2013); however, most studies focused on sugarcane and soybeans and evaluation of other feedstock options and processes relevant to a tropical climate is still limited. Given such paucity, the present study

makes contribution by examining environmental impacts of advanced bioethanol option using a tropical fodder crop of banagrass, which is one of the highest yielding grasses. Because of its robust growth, banagrass has been considered as potential bioenergy crop in a number of countries including Thailand, the Philippines, China, Australia, and the United States (Holm, 2010; Manila Times, 2011; Changsorn, 2012, and Jessen, 2012). In particular, this study examines a novel green-processing technology and compares it with conventional ethanol processing which uses dried feedstock with no fungal co-product.

II. GOALS AND SCOPING

We quantify the well-to-pump and well-to-wheel life-cycle energy and GHG emissions of banagrass-derived bioethanol and to analyze this vis-à-vis conventional gasoline and existing first and second generation bioethanol options. The LCA analysis was performed considering two ethanol production technologies: (i) Green-processing, which utilizes moisture-rich premature harvest of banagrass under coordinated harvesting and processing. Under this just-in-time processing, in which wet banagrass is immediately converted to ethanol with an option to use its juice for co-production of high value biomass protein. (ii) Dry processing, which utilizes mature and dried harvest of banagrass, that is converted to ethanol with no co-product of biomass protein. We compare energy and greenhouse gas footprint of green-processing with and without co-product generation and dried processing of banagrass. The functional unit used in this study was 10 000 MJ of ethanol at the pump. For the well-to-wheel analysis, the fuel economy of a flex fuel vehicle (FFV) was assumed to be 10.2 km/l (24 miles-per-gasoline equivalent gallon) (GREET, 2012) and the functional unit is the fuel needed to drive 1 km of distance.

III. METHODOLOGY

A. System boundaries

The system boundaries include all material inputs used during various stages of ethanol production life-cycle: feedstock production, biomass transportation, ethanol production and ethanol distribution (Figure 1). Relative mass energy and economics (RMEE) method with a cut-off value of 0.01 was used to determine system boundary (Raynolds *et al.*, 2000). RMEE assesses the contribution of each process input in terms of mass, energy, and economic value (relative to those of functional unit), and ensures that the upstream process related to those inputs that are found to be above this cut-off will be included in the analysis. The economic values of inputs were estimated based on published materials (fertilizers: USDA (2012); pesticides: Grube *et al.* (2011); chemicals: Maclean and Spatari (2009); and Kumar and Murthy (2011)). Fuel prices were based on USDOE (2012). The heating values of fuels as reported in the GREET (2012) were used. Some inputs such as fuel use during distribution and planting, were found to be outside the system boundary, and were included in the analysis. It is assumed non-prime and non-unique land under the Agricultural Lands of Importance to the State of Hawaii (ALISH) classification will be used to cultivate banagrass, which precludes the conversion of forest land and crowding out of current agricultural production within prime land. Also, good agricultural practices will be used to maintain soil organic carbon content at the current level to avoid net emissions related to direct land use emissions (Figure 2). Hence the emissions related to direct and indirect land use changes are excluded in this study. Furthermore, any production of capital goods including machinery is excluded in this study as these processes fall outside the RMEE boundary.

B. Life cycle inventory

Inventory data are drawn from publically available sources including scientific journal articles and a transportation energy focused life-cycle assessment tool, the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET 1–2012) model. Table I summarizes sources used to obtain data used in this study.
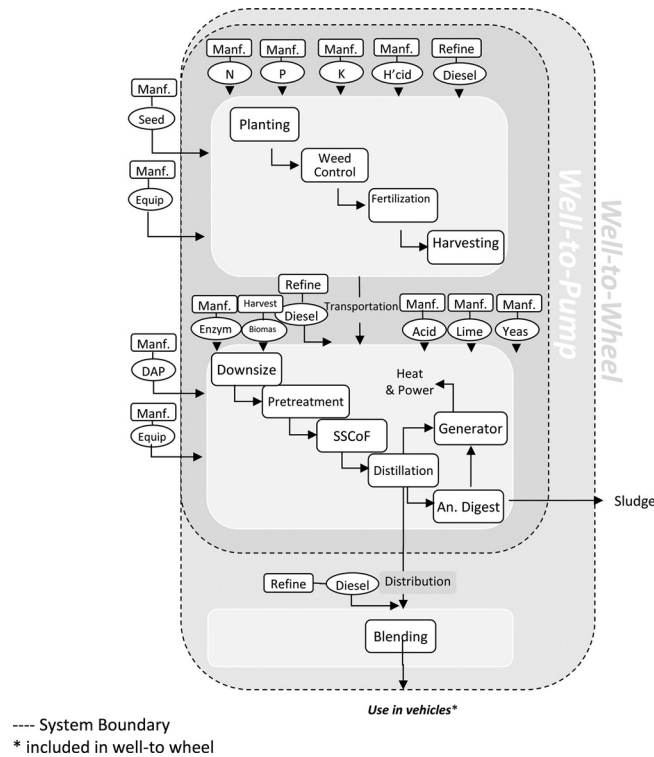
FIG. 1. System boundary for banagrass to ethanol production.

C. Process description

1. Feedstock production

Banagrass, also known as Napier or Elephant grass, is one of the highest yielding C4 plants, native to the subtropical African country of Zimbabwe (Skerman and Riveros, 1990). It is a perennial crop which matures within seven to eight months and yields multiple ratoon harvests. Since its original introduction from Australia to Hawaii in the mid-1970s, banagrass has been used locally as windbreaks and more recently has been studied as a bioethanol feedstock option (for resources potential and economic feasibility, see for example: Keffer *et al.*, 2009; Black and Veatch, 2010; and Tran *et al.*, 2011). The potential yield of banagrass depends on
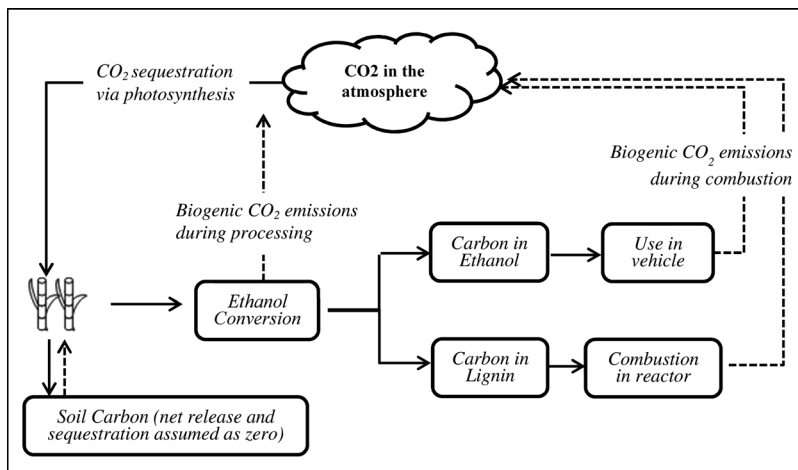

FIG. 2. Biogenic carbon balance during ethanol production. Adapted from Juneja *et al.*, 2013.

TABLE I. Life-cycle inventory sources.

Processes	Items	Sources
Feedstock production	Agricultural machinery operation and fuel demand	Downs and Hansen (1998)
	Fertilizers and chemical application rates	Osgood *et al*. (1996)
	Emissions related to fertilizers and chemical production; emissions factor for agricultural machinery fuel use	GREET (2012)
	Direct and indirect land emissions	IPCC (2006)
Ethanol Production	Electricity generation	DBEDT (2010)
	Chemicals and yeast (Ca(OH)$_2$, Sulfuric Acid), yeast) production	GREET (2012); EuLA (2007); MacLean and Spatari (2009); and Kumar and Murthy (2011)
	Cellulase production	GREET (2012);[a] MacLean and Spatari (2009); and Novozymes (2012)[a]
	Emissions related to co-product generation	GREET (2012)
Biomass transport and ethanol distribution	Heavy-duty truck fuel economy; emissions related to fuel combustion, refinery and crude oil production	GREET (2012)

[a]Used for sensitivity analysis.

many factors including environmental conditions such as climate and soil, together with management choices including irrigation and fertilization. Under rainfed condition, an average dry matter yield of banagrass ranges from 18.4 tons/ha/yr (under isomesic soil temperature and udic soil moisture regimes) to 60.0 dry tons/ha/yr (under isohyperthermic soil temperature and udic soil moisture regimes) while under irrigation, it ranges from 15.7 dry tons/ha/yr (under isomesic soil temperature and ustic or udic soil moisture regimes) to 100 dry tons/ha/yr (under isohyperthermic soil temperature and aridic soil moisture regimes) (Black and Veatch, 2010). This study assumed rain-fed production of banagrass in Hawaii. Table II summarizes major assumptions used for feedstock production.

The cultivation process of banagrass is similar to that of sugarcane because of similar morphology. The cultivation process include: (i) soil preparation; (ii) seed production; (iii) planting; (iv) fertilization; (v) weed control; (vi) irrigation (if applicable); and (vii) harvesting and transportation. Although no commercial scale banagrass production has taken place in Hawaii, a number of field trials have demonstrated that conventional sugarcane machinery may be used with minor modifications and these provide important insights regarding the likely banagrass

TABLE II. Major assumptions regarding feedstock production.

Categories	Values	Sources
Banagrass yield	48.2 dry tons/ha/yr	Tran *et al*. (2011)
Harvesting efficiency	73%	Osgood *et al*. (1996)
N fertilizer use	227 kg/ha/yr (planting)	Osgood *et al*. (1996)
	202 kg/ha/yr (ratoon)	
P$_2$O$_5$ fertilizer use	125 kg/ha/yr (planting)	Osgood *et al*. (1996)
	202 kg/ha/yr (ratoon)	
K$_2$O fertilizer use	208 kg/ha/yr (planting)	Osgood *et al*. (1996)
	0 kg/ha/yr (ratoon)	
Lime application	None	Sakuda (2011)
Irrigation requirement	None	Tran *et al*. (2011)
Zoning	Non-prime non-unique agricultural land	Black and Veatch (2010)

production at a commercial scale (Kinoshita and Zhou, 1999). Due to data limitations, herbicide application in banagrass production was estimated based on the sugarcane figures available in GREET (2012), assuming that herbicide use is the same as for sugarcane in planting years and is minimal during ratoon years (Hubbard *et al.*, 1993). For the current study, the fertilizer application rate was taken from a previous field trial (Osgood *et al.*, 1996).

2. Farm to plant feedstock transportation

In this study, it is assumed that a bioethanol production plant will have a biomass processing capacity of about 250 000 tons of feedstock (at 7% moisture) annually with 330 days of operation. Existing studies of resource availability have shown that Hawaii has 329 600 ha (814 500 acres) of non-prime and non-unique land under the ALISH categorization, which can be used for dedicated energy crop cultivation (Black and Veatch, 2010). Assuming a rain-fed yield of 48.2 dry tons/ha/yr of banagrass with 73% harvesting efficiency, the land area required to produce 704.5 dry tons of feedstock per day with 330 days of operation is estimated at approximately 6600 ha (16 300 acres) per year, similar to the existing scale of commercial sugarcane production in Hawaii estimated at 6430 ha (15 900 acres) in 2012 (USDA, 2013). Hence, the existing non-prime, non-unique agricultural land is sufficient to support this production scale. Upon harvest, biomass is assumed to be transported to a bioethanol processing plant via ground transportation. Feedstock is hauled using heavy-duty trucks, which can transport up to 15.4 wet tons of biomass per trip (GREET, 2012). Required transportation distance was calculated using Eq. (1) (Aden *et al.*, 2002 and Kumar and Murthy, 2012),

$$\alpha = \frac{\delta\,banagrass}{\beta\,banagrass * \gamma\,cropland * \gamma\,availability * \gamma\,collect}, \tag{1}$$

where α. is the total area served by feedstock transportation, $\delta\,banagrass$ is the total biomass needed for bioethanol production, $\beta\,banagrass$ is annual yield, and $\gamma\,cropland$ is the ratio of farmland to the overall area including roads and non-farm lands. The $\gamma\,cropland$ is assumed to be 0.6 based on Kumar and Murthy (2012). The $\gamma\,availability$ is the fraction of farmland which may grow banagrass, as opposed to other crops. The $\gamma\,availability$ is assumed to be 1 based on the fact that production of banagrass takes place on non-prime non-unique agricultural lands as opposed to prime-agricultural land currently used for other agricultural crop production. While sizable fallow land area exists within non-prime, non-unique agricultural land on the island of Hawaii (Melrose and Delparte, 2012), it is assumed that all agricultural land within the vicinity could be used for banagrass production purposes. The $\gamma\,collect$ is the fraction of banagrass actually harvested as opposed to yield, which is assumed as 0.73 based on the harvesting efficiency recorded in Osgood *et al.* (1996). Based on these values, the distance needed to collect banagrass (i.e., the radius of a circle, assuming that a bioethanol plant would be sited at the center of the area) is estimated as 5.9 km (or approximately 12 km per around trip). T life-cycle energy requirements and emission factors of a heavy-duty transportation truck operation were also taken from GREET (2012).

3. Banagrass-to-ethanol conversion

Lignocellulosic biomass may be converted into biofuel by a variety of technologies including biochemical, thermochemical, and combined pathways. This study examines a biochemical pathway based on simultaneous saccharification and co-fermentation (SSCoF) and using dilute acid pretreatment, comparing two options of green and dry processing of banagrass to ethanol conversion. Green-processing uses just-in-time harvesting and processing of banagrass in which freshly harvested grass may be converted to ethanol without extensive drying and storage. Using this novel front-end operation, banagrass may also be processed separately to obtain plant juice which can be used to grow protein-rich fungal biomass as co-product. Green-processing is considered particularly suitable in a tropical climate where high humidity and frequent rain precludes the possibility of extensive field drying. On the other hand, dry processing is based on

conventional technology in which dried feedstock (typically via field drying but via biomass field drying in the case of Hawaii due to climatic condition) is proceeded with no production of fungal co-product. For the dry processing option, it is assumed that drying system requires a minimal consumption of fossil fuel (i.e., 5% of energy needed) to sustain flame for safety based on communication with a vendor. For dry processing, the use of fossil fuel fired dryer is not a feasible option due to high GHG emissions associated with such option. It is assumed that biomass used for the drying purpose are field dried, thus no additional energy is included. The life-cycle energy and emissions associated with growing, harvesting and transportation of biomass materials are included in the analysis. In both cases banagrass is converted using dilute sulfuric acid pretreatment and SSCoF. The basic process model follows that of Kumar and Murthy (2011), with a processing capacity of 250 000 tons/yr of tall fescue with 20% solid loading built using SuperPro Designer. Further modification was introduced for the green-processing option by including additional processes of screw-pressing, fungal cultivation, dewatering, and drying for co-product generation. The detailed model description of dry processing used for this study is provided elsewhere (Kumar and Murthy, 2011). The schematic of green processing technology for bioethanol production is provided in Figure 2 which involves juicing of fresh that enables production of protein rich fungal co-product generation—for the details of process, please refer to (Takara and Khanal, 2011). The composition of mature banagrass used in this analysis was assumed as 37% cellulose, 22% hemicellulose, 21% lignin, 8.3% ash, and 13% extractives on a dry weight basis (Takara, 2012). Pretreatment conditions are provided in Table III.

The innovative concept of green or wet processing is based on the use of fresh crops with high moisture content. In this front end operation, feedstock with a moisture content of about 60%–70% is chopped and juiced for subsequent co-product generation (Figure 3). Banagrass juice is known to contain essential amino acids such as lysine and methionine, together with glucose, crude protein, and lipids, which provide suitable substrate for microbial feed production (Takara and Khanal, 2011).

Co-product generation is based on the cultivation of *Rhizopus microsporus var. oligosporus*, a commonly used ingredient of the fermented Indonesian soy product tempeh. Fungal cultivation of *R. oligosporus* has been studied extensively in the context of co-product generation and waste water treatment (Jasti *et al.*, 2008; Sankaran *et al.*, 2008; Nitayavardhana and Khanal, 2010; Takara and Khanal, 2011; and van Leeuwen *et al.*, 2012). This study assumes that *R. oligosporus* will be grown in a stirred tank reactor with operating conditions (energy needed for agitation and aeration) equivalent to that of cellulase production (Humbird *et al.*, 2011). The grown edible fungal biomass will be dewatered using a decanter centrifuge and dried in a biomass-fired rotary drying system. Given the lack of data on fungi biomass drying,

TABLE III. Pretreatment conditions and efficiencies adopted for this study.

	Green processing	Dry processing
Acid concentration (% sulfuric acid)[a]	5	5
Temperature ($^\circ$C)[a]	120	120
Pressure during pretreatment (kPa)[a]	199	199
Residence time (min)[a]	45	30
Solid loading (%)[b]	20	20
Cellulose + 0.111 H_2O = 1.111 Glucose (%)[a]	11	5
Hemicellulose + 0.136 H_2O = 1.136 Xylose (%)[a]	99	55
Lignin - > Soluble lignin (%)[b]	5	5
Xylose - > 0.64 furfural + 0.36 H_2O (%)[b]	5	5
Glucose - > 0.7 HMF + 0.3 H_2O (%)[b]	5	5

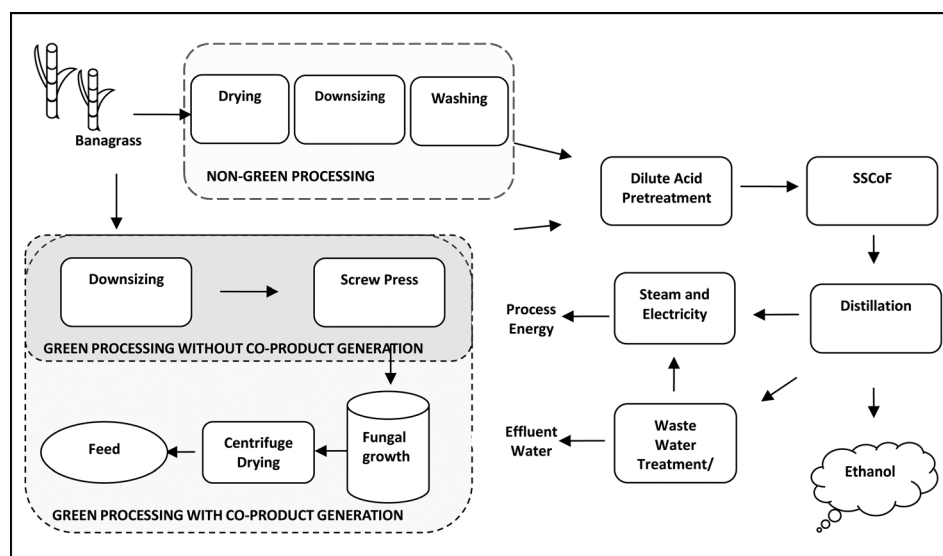[a]Takara (2012).
[b]Kumar and Murthy (2011).

FIG. 3. Process design of green and dry processing of banagrass to ethanol.

it was assumed that the energy requirement for fungal drying was equivalent to that of the Distillers Dried Grains with Solubles drying system reported by Kwiatkowski *et al.* (2006). Based on laboratory scale data available from Takara (2012), it is estimated that 6.8 g of fungi may be produced per liter of banagrass juice.

After the juice extraction, the biomass is processed as in the case of dry processing technology using dilute acid pretreatment followed by SSCoF, as described in Kumar and Murthy (2011). Dilute acid pretreatment using sulfuric acid is one of the commonly used pretreatment methods to reduce the biomass recalcitrance and improve the subsequent hydrolysis efficiency, although the degradation of carbohydrates and the formation of inhibitors (such as furfural, hydroxymethylfurfural (HMF), and acetic acid) during the process require additional unit operations such as conditioning. In the process model, banagrass was pretreated at optimal pretreatment conditions (Table III) based on lab scale trials (Takara, 2012). Upon dilute acid pretreatment, banagrass will go through over-liming at a pH of 10 to reduce inhibitor activities, thereby increasing subsequent fermentation efficiency.

The conditioned biomass was converted to ethanol the SSCoF process, under conditions that are the same for both green and dry processing options (Table IV). The hydrolysis efficiencies were assumed to be equal to efficiencies obtained in the laboratory experiments (81% for cellulose and 99% for hemicellulose in the case of dry processing, and 83% for cellulose and 99% for hemicellulose in the case of green-processing) (Takara, 2012). The enzyme loading was assumed as 15 FPU/g of cellulose with an activity level of 600 FPU/g of protein (with

TABLE IV. SSCoF condition adopted for this study.

	Green Processing	Dry Processing
Temperature ($^\circ$C)[a]	35	35
Enzyme Loading (FPU/g of cellulose)[a]	15	15
Residence Time (days)[a]	5	5
Cellulose $+ 0.111\ H_2O = 1.111$ Glucose (%)[b]	83	81
Hemicellulose $+ 0.136\ H_2O = 1.136$ Xylose (%)[b]	99	99
Glucose $-> 0.489\ CO_2 + 0.511$ Ethanol (%)[a]	95	95
Xylose $-> 0.489\ CO_2 + 0.511$ Ethanol (%)[a]	70	70

[a]Kumar and Murthy (2011).
[b]Takara (2012).

10% protein content in slurry) (Kazi *et al.*, 2010 and Kumar and Murthy, 2011). Glucose and xylose fermentation efficiencies were assumed to be 95% and 70%, respectively.

Anhydrous ethanol was recovered after fermentation using a combination of distillation columns and molecular sieves. The co-product stream with lignin-rich residues was recycled as a source of heat power. Waste water treatment involves a series of anerobic and aerobic digesters. Methane is produced at a rate of 0.24 kg/kg of chemical oxygen demand removal (Barta *et al.*, 2010). Electricity generation capacity was estimated based on the heating value of waste stream components, assuming 30% efficiency in power generation, with further described in Kumar and Murthy (2011).

4. Ethanol distribution

From a production plant, ethanol is transported to blending facilities via ground transportation using heavy duty trucks. On the island of Hawaii, ethanol-to-gasoline blending takes place at three locations, all of which may be accessed within roughly 45 km of linear distance from anywhere on the island. Therefore, this study assumes that ethanol is transported 45 km using trucks fueled by diesel. The emission factors for ethanol distribution are based on GREET (2012) using 100% truck transport. This study assumes no inter-island shipment of bioethanol within Hawaii.

D. Co-product allocation

The energy from lignin residues is a co-product during ethanol production process in both green and dry processing technologies, whereas fungal protein is a co-product produced during green processing only. To allocate the energy use and emissions produced among product and co-products, the system expansion approach was used in this study (Kim and Dale, 2002). For the protein-rich fungal biomass co-product, it is assumed that the fungi-derived feed will replace sbean meal used commonly as a conventional feed ingredient. This study allocates materials and energy use among soy oil and soy bean meal based on mass (GREET, 2012). After displacing the thermal energy needs of the processing plant with the lignin energy, any excess electricity produced by lignin was assumed to replace the current electricity generation mix on the island of Hawaii (69% petroleum, 14% geothermal, 12% wind, 5% hydro, and 1% solar uses (DBEDT, 2010)).

IV. RESULTS AND DISCUSSION

A. Life-cycle energy use

Model results indicate that process energy and chemical input requirements to produce one functional unit (10 000 MJ of ethanol) differ among green processing with or without co-product and dry processing options. While the differences are found to be small for all inputs used during feedstock production and transport & distribution phases, sizable differences in energy and input use exists in ethanol conversion (Table V). The small differences during agricultural production and biomass transportation are because of different ethanol yields from green and dry technologies of ethanol production, which results in slightly different amounts of feedstock required to produce same functional unit. Ethanol yields were estimated at 0.27 l/kg (green processing with fungal co-product), 0.27 l/kg (green processing without co-product), and 0.29 l/kg (dry-processing) of feedstock, respectively.

During ethanol production process, the difference is particularly notable in power consumption and production, with the green-processing consuming 60 kW h more power on a gross basis than the dry processing option per functional unit. The higher gross power consumption in green-processing with co-product is primarily due to the additional power requirements in aeration and agitation operations during fungal co-product production. Both green processing with and without co-product need additional process steam due to an increased use of an evaporator to handle the additional waste water stream. Additional process team requirements lower the surplus energy available for electricity production. Other inputs, including cellulase, yeast, lime, and gasoline, are found to be similar for all three options.

TABLE V. Resources and energy use in green and dry ethanol processing options (per 10 000 MJ ethanol).

	Green processing with co-product	Green processing without co-product	Dry processing
Feedstock requirement (dry tons)	1.8	1.8	1.6
Sulfuric acid (kg)	330	330	330
Cellulase (kg)	120	120	130
Yeast (kg)	1.4	1.4	1.3
$Ca(OH)_2$ (kg)	200	200	200
Gasoline (kg)	3.7	3.7	3.7
Heat/cooling requirement			
Steam (kg)	3300	3300	2800
Cooling water (kg)	197 000	192 000	196 000
Chilled water (kg)	330	330	360
Gross power consumption[a] (kW h)	390	350	330
Power produced from lignin energy (kW h)	88	120	250
Net power consumption (kW h)	302	230	80

[a]Calculated outside of the SuperPro Designer.

Net energy value (NEV) and net energy ratios (NERs), commonly used terms in LCA studies, were calculated for both cases using Eqs. (2) and (3). The concept of net energy balance has been used widely to measure the potential energy gains and losses that can be made by the use of biofuels (Schmer *et al.*, 2008; Khatiwada and Silveira, 2009; and Bureau *et al.*, 2010), though NER or NEV alone cannot be used to compare alternative fuel options without considering the quality of fuel (Kumar and Murthy, 2012). NEV is calculated as the difference between the energy content of the fuel (E_{output}) and the amount of fossil fuel used in production (E_{input}), after considering fossil energy allocated for co-product generation ($E_{coproduct}$) (Farrell *et al.*, 2006). A positive NEV indicates relative fossil energy gains whereas negative NEV indicates that more fossil fuel energy is needed to be produced than the energy contained in the final product. Similarly, NER value higher than one indicates energy gains

$$\text{NEV} = E_{Output} + E_{co-prroduct} - E_{input},\tag{2}$$

$$\text{NER} = \frac{E_{output} + Ecoproduct}{E_{input}}.\tag{3}$$

The results indicate that net energy values are positive for all cases: green-processing with co-product (1800 MJ/functional unit), green-processing without co-product (2400 MJ) and dry processing (2800 MJ/functional unit) (Table VI). NEV found in this study for both technologies (3.8 MJ/l ethanol, 5.3 MJ/l ethanol, and 5.9 MJ/l ethanol for green-processing with co-product, green-processing without co-product and dry processing, respectively) were relatively lower

TABLE VI. Net energy balance of banagrass-based ethanol production and gasoline.

	Green-processing with co-product	Green-processing without co-product	Dry processing	Gasoline (GREET, 2012)
Total life-cycle fossil energy consumption (per 10 000 MJ)	8200 MJ	7600 MJ	7200 MJ	12 000 MJ
NEV (per 10 000 MJ)	1800 MJ	2400 MJ	2800MJ	−2100MJ
NEV (per liter)	3.8 MJ	5.2 MJ	5.9 MJ	−6.6 MJ
NER	1.2	1.3	1.4	0.8

compared to values reported in lignocellulosic ethanol studies (21.5 MJ/l ethanol for switchgrass in Schmer *et al.* (2008); 12.89 MJ/l ethanol for tall fescue in Kumar and Murthy (2011)).

The difference in the NEV can be contributed by several factors including biomass yields, different levels of chemicals and energy used during ethanol conversions, and process efficiencies. The values of net energy ratio in all cases were found to more than one, indicating energy gains that can be made in these options. Fossil energy use related to agricultural machinery use and agrochemical use were 370 MJ and 810 MJ, respectively, per 10 000 MJ of ethanol produced using green processing technology with and without co-product and 340 MJ and 760 MJ, respectively, per 10 000 MJ of ethanol produced using dry processing technology. Life-cycle fossil fuel use related to ethanol processing per functional unit are 2700 MJ (net process power with co-product) and 2200 MJ (net process power without co-product), 2900 MJ (enzyme), 880 MJ (Calcium Hydroxide $Ca(OH)_2$), 200 MJ (sulfuric acid (H_2SO_4)), 55 MJ (yeast), 37 MJ (gasoline) for green processing, and 730 MJ (net process power), 3200 MJ (enzyme), 880 MJ ($Ca(OH)_2$), 201 MJ (H_2SO_4), 52 MJ (yeast), 37 MJ (gasoline) for dry processing, respectively. Those related to biomass transportation and ethanol distribution per functional unit were 150 MJ and 64 MJ for green-processing with and without co-product and 140 MJ and 64 MJ for dry processing.

B. Life-cycle GHG emissions

The GHG emissions produced during various stages of life cycle of ethanol production from banagrass using green and dry processing technologies are presented in Table VII. Net GHG emissions are positive for both green and dry processing options, estimated as 144 000 gCO_2-eq. (green processing with co-product), 90 600gCO_2-eq. (green processing without co-product), and 59 100 gCO_2-eq. (dry processing without co-product) per 10 000 MJ ethanol, respectively. The emissions are 22%, 51%, and 68% less than those from gasoline production (185 000 gCO_2-eq. per 10 000 MJ of gasoline), respectively. The emission "hot-spots" identified are presented in Figures 4 and 5.

Using IPCC (2006) default values for direct and indirect land emissions, nitrous oxide emissions from land application of fertilizer accounted for the largest fraction (39%) during banagrass production stage, followed by emissions related to production of nitrogen fertilizer (34%) (Fig. 4). The significant contribution of nitrous oxide emissions observed during banagrass production were similar to emissions observed during sugarcane production by Renouf and Wegener (2007), which estimated that 59% of GHG emissions related to sugarcane production and sugar processing are from nitrous oxide emissions due to soil nitrification and denitrification.

During ethanol conversion, emissions associated with the production of enzymes contribute to the highest portion of total GHG emissions for both green and dry processing. The contribution of enzyme use per functional unit were 270 $kgCO_2$-eq. for green processing with

TABLE VII. GHG emissions produced during ethanol production stages using green and dry processing per 10 000 MJ.

	Green processing with co-product	Green processing without co-product	Dry processing
Feedstock production (gCO_2-eq.)	144 000	144 000	134 000
Transportation (gCO_2-eq.)	11 700	11 700	10 900
Ethanol processing (gCO_2-eq.)[a]	696 000	643 000	619 000
Distribution (gCO_2-eq.)	4990	4990	4990
Co-product credit for fungal biomass (gCO_2-eq.)	3350	n.a.	n.a.
CO_2 sequestered in fuel (gCO_2-eq.)	709 800	709 800	709 800
Total life-cycle GHG emissions (gCO_2-eq.)[b]	144 000	90 600	59 100

[a]After accounting for co-product lignin energy.
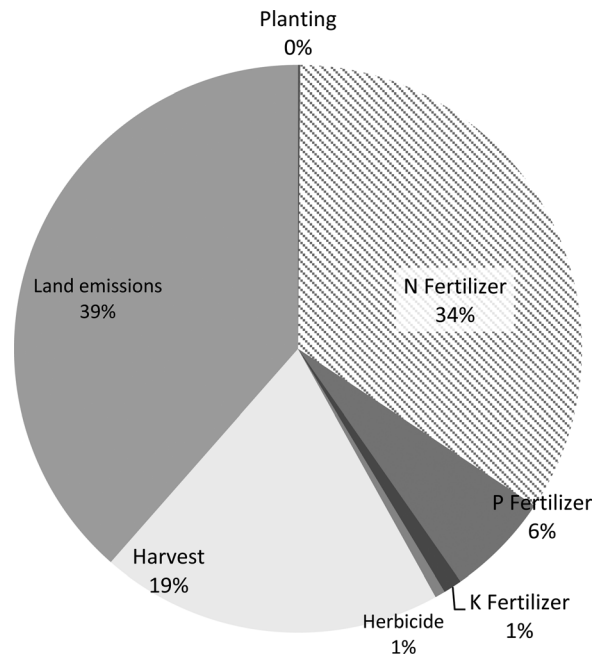[b]May not add up due to rounding.

FIG. 4. GHG emissions breakdown of banagrass production.

co-product, 270 kgCO$_2$-eq. for green processing without co-product and 290 kgCO$_2$-eq. for dry processing. These figures are higher than in previous studies such as that done by MacLean and Spatari (2009) which reported figures between 33 kgCO$_2$-eq. and 36 gCO$_2$-eq./10 000 MJ of ethanol and that of Dunn *et al.* (2012) which estimated 46 kgCO$_2$-eq./10 000 MJ of ethanol, but similar to the values reported in Kumar and Murthy (2011) estimated at 278 kgCO$_2$-eq. to 340 kgCO$_2$-eq./10 000 MJ of ethanol. This is due to the fact that the former studies assumed the lower enzyme dosage of 9.2 g to 9.6 g per kg of biomass (MacLean and Spatari, 2009), and 10 g per kg of biomass (Dunn *et al.*, 2012), whereas the latter assumed a higher enzyme dosage of 63 g to 72 g per dry kg of biomass based on laboratory measurement of purchased enzyme cocktail (Kumar and Murthy, 2011). In the present study, the enzymes used were estimated as
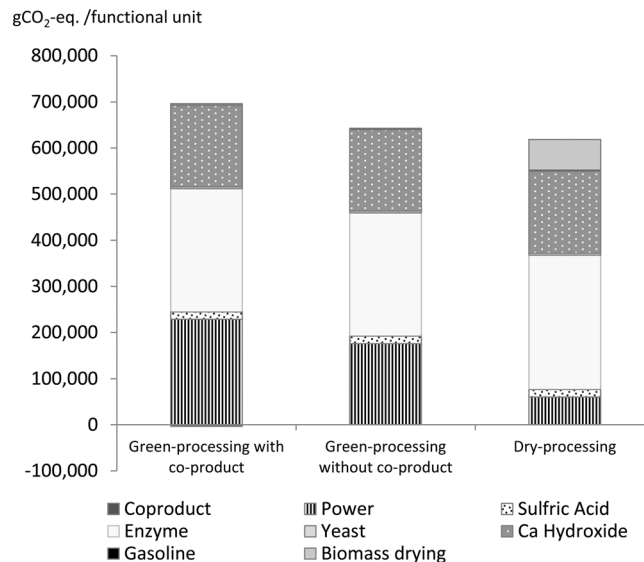

FIG. 5. Life-cycle GHG emissions from ethanol processing.

120 kg/10 000 MJ (67 g/kg of biomass) for green processing with and without co-product and 130 kg/10 000 MJ (78 g/kg of biomass in dry processing, respectively. Since enzyme dosage and emissions during its production process is vary considerably among different studies (Dunn *et al.*, 2012), sensitivity analysis was performed and is reported later.

GHG emission related to calcium hydroxide production is also an important contributor during ethanol processing, estimated at 180 kgCO$_2$-eq./10 000 MJ for green processing with and without co-product and 180 kgCO$_2$-eq./10 000 MJ for dry processing. Calcium hydroxide is used as the over-liming agent to remove the toxicity of inhibitors formed during pretreatment. The relatively high contribution estimated in this study stems primarily from the higher sulfuric acid concentration (5%) adopted for this study, as compared to existing techno-economic studies based on alternative feedstock options including Aden *et al.* (2002) which adopted the concentration of 1% acid for corn stover and Kumar and Murthy (2011) which adopted the concentration of 1% acid for tall fescue. Further optimization of pretreatment conditions could lower GHG emissions during these steps.

The green-processing with co-product option is found to produce protein-rich fungal product at a rate of 1380 tons of fungal co-product (9.4 kg/functional unit) with a moisture content of 11%. Assuming the feed may be sold at an equivalent price with soybean meal, this new product stream will generate revenue of $280/dry tons of fungi biomass (Nitayavardhana and Khanal, 2010). Further assuming that this co-product will replace soybean meal, with the life-cycle GHG emissions of 353 gCO$_2$-eq./kg of soybean meal, it yields an equivalent of 3350 gCO$_2$-eq./functional unit of GHG emissions replacement (GREET, 2012). Further optimization of fungal biomass yield and process integration will likely improve the GHG emissions impact of the green-processing option. The results suggest that the fungal biomass co-product is more energy intensive than the product it is meant to replace. The difference in power and steam use, for example, is estimated to add 168 000 g of CO$_2$eq. per functional unit for green-processing owing to higher energy needs during fungal cultivation. Green processing with fungal biomass co-product, therefore, appears less favorable than dry processing and stand-alone green processing without a fungal biomass co-product stream.

C. Well-to-wheel analysis

To further examine our results in comparison with existing studies, this section conducts well-to-wheel assessment, assuming that banagrass-derived ethanol will be used in a Flex-Fuel Vehicle as E85. Tail-pipe emissions related to E85 and fuel economy were assumed based on the data provided in GREET, 2012. The results of well-to-wheel analysis show that the use of E85 emits 280 gCO$_2$-eq., 260 gCO$_2$-eq., and 250 gCO$_2$-eq. per km driven using ethanol produced from green processing with co-product, green processing without co-product and dry-processing, respectively. As illustrated in Figure 6, well-to-wheel emissions estimated in the current study were relatively higher than those reported in other bioethanol LCA studies: miscanthus estimated at 22 gCO$_2$-eq./km (GREET, 2012), corn stover at 75 gCO$_2$-eq. (GREET, 2012) to 95 gCO$_2$-eq./km (Spatari *et al.*, 2005), switchgrass at 82 gCO$_2$-eq./km (GREET, 2012), poplar at 140 gCO$_2$-eq./km (Gonzalez-Garcia *et al.*, 2010) and flax at 180 gCO$_2$-eq. /km (Gonzalez-Garcia *et al.*, 2010). As discussed earlier, the results are different because of different feedstock compositions, chemical inputs, process conditions and efficiencies. Both green (with or without fungal co-product) and dry processing technologies had lower life-cycle GHG emissions than gasoline estimated at 290 gCO$_2$-eq./km (GREET, 2012), but had higher GHG emissions than corn-derived ethanol at 220 gCO$_2$-eq./km (GREET, 2012).

Note: Emissions figures are adjusted based on the fuel economy reported in GREET (2012).

While the existing studies generally report lower well-to-wheel GHG emissions, it is important to note that these options may not be as favorable, given specific agro-environmental and socioeconomic conditions of Hawaii. In particular, many alternative crops evaluated in the European and continental United States contexts (i.e., miscanthus, alfalfa, switchgrass, poplar, hemp, flax) will unlikely achieve high yields in Hawaii due to local conditions such as pests/
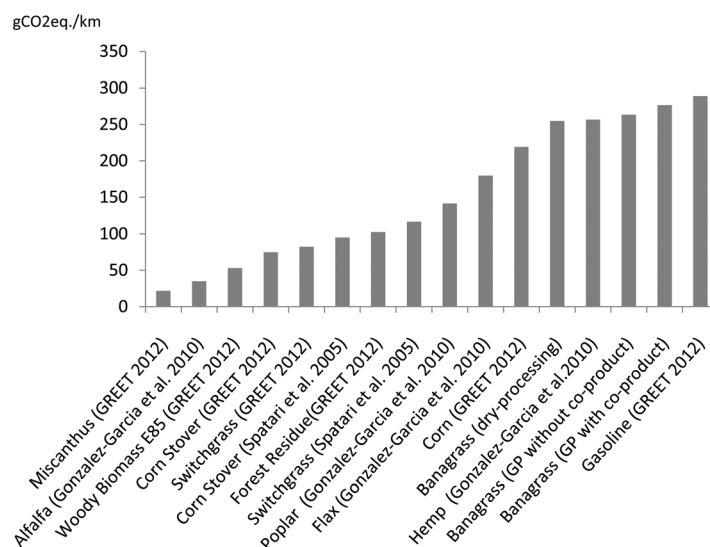
FIG. 6. Comparison of well-to-wheel GHG emissions with existing studies (in gCO$_2$-eq./km).

disease, temperature (i.e., relatively high year-around day and night temperature) and short photoperiod from October to March which may increase harvesting frequency. The use of genetically modified crops, such as corn, also faces a number of local regulatory restrictions (McAvoy, 2014). High yielding banagrass has been identified as the most economically viable feedstock option in Hawaii (Black and Veatch, 2010 and Tran *et al.*, 2011). Therefore, from the standpoint of production cost and agro-environment conditions, banagrass will likely be a favorable option as compared to the existing lignocellulosic feedstock options.

D. Sensitivity analysis

Uncertainty is inherent in elements of LCA, which requires cautious examination (McKone *et al.*, 2011). In the case of biofuel LCA studies, the choices of system boundary, co-product accounting methods, and fuel-economy assumptions are major factors that impact the analysis outcomes (Luo *et al.*, 2009 and Singh *et al.*, 2010). Furthermore, continued research and development and commercialization efforts of lignocellulosic bioethanol means that technology is hardly static and uniform, and that temporal and technological variations will likely be a major contributor to the uncertainty of its life-cycle environmental impacts. Given the inherent uncertainty in bioethanol LCA, sensitivity analysis offers an important insight regarding the likely variation of GHG emissions and energy demand. By analyzing a range of key parameters, sensitivity analysis helps to avoid drawing false conclusions regarding life-cycle impacts solely based on default values (Cherubini *et al.*, 2009). Sensitivity analysis was performed with regards to enzyme technology (by varying enzyme loading and emissions factors associated with the production of enzymes).

Figure 7 illustrates the sensitivity analyses results of enzyme-related parameters for the green-processing with co-product and dry-processing cases. As expected, well-to-wheel GHG emissions of both green and dry processing options decreased with decreases in enzyme loading. Changes in emission factors associated with enzyme production based on different studies (2260 gCO$_2$-eq. per kg of enzyme by MacLean and Spatari (2009), 3480 gCO$_2$-eq. by GREET (2012), and 8000 gCO$_2$-eq. by Novozymes (2012)) resulted in a wide range of net GHG emissions.

First, using higher emission factor suggested by Novozymes (2012), both green and dry processed E85 fuel production resulted in net GHG emissions higher than those of gasoline. GHG emissions increased from 250 gCO$_2$-eq./km (10 g of enzyme/kg biomass) to 490 gCO$_2$-eq./km (80 g enzyme/kg of biomass) for green processing, and 220 gCO$_2$-eq./km (10 g of
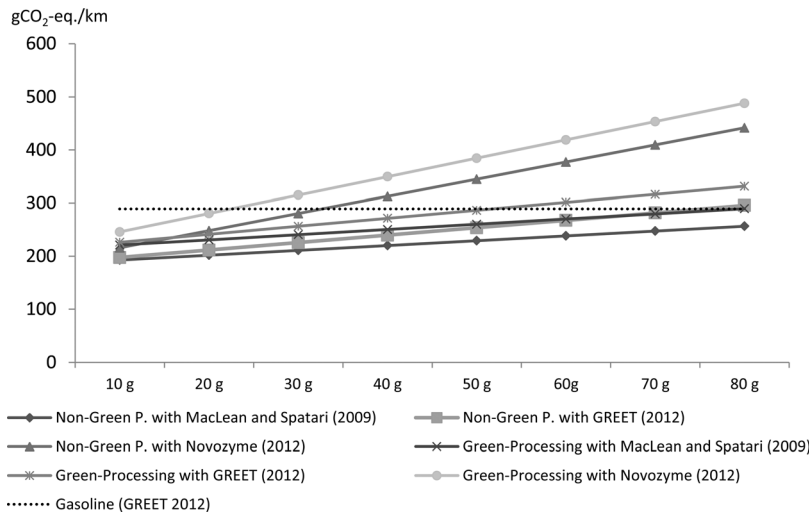
FIG. 7. Sensitivity analysis with different enzyme loading (g of cellulase/dry kg of biomass) and emissions factors.

enzyme/kg of biomass) to 440 gCO_2-eq./km (80 g of enzyme/kg of biomass) for dry processing. Using GREET's (2012) unit emissions value, emissions increased from 230 gCO_2-eq./km (10 g of enzyme per kg of biomass) to 330 gCO_2-eq./km (80 g of enzyme/kg of biomass) for green processing, and 200 gCO_2-eq./km (10 g of enzyme/kg of biomass and 300 gCO_2-eq./km (80 g of enzyme/kg of biomass) for dry processing. Based on the values reported in McLean and Spatari (2009), emissions were estimated at 220 gCO_2-eq./km (10 g of enzyme/kg of biomass) to 290 gCO_2-eq. for green processing and 190 gCO_2-eq./km (10 g of enzyme/kg of biomass) and 260 gCO_2-eq./km (80 g of enzyme/kg of biomass). The wide range of variation observed in this study confirms the general experts' view that enzyme loading and emissions related to its production are highly uncertain (Dunn *et al.*, 2012 and McLean and Spatari, 2009). Further optimization of enzyme production process, together with improvements in enzyme activity and saccharification efficiency will likely improve these emission impacts, and it is generally difficult to draw precise conclusions given the likely range of enzyme related life-cycle GHG emissions.

Further sensitivity analysis was conducted to estimate the impacts on co-product allocation methods. In the base case, the production of fungal biomass co-product resulted in a displacement of soybean meal, which accounted for an equivalent of 3350 gCO_2-eq./functional unit, and the total well-to-pump GHG emissions per functional unit was estimated at 143 000 gCO_2-eq. Based on mass allocation methods, 98% and 2% of energy used and emissions produced during ethanol processing were allocated to ethanol and fungal biomass co-product, respectively, which resulted in the total well-to-pump GHG emissions of 129 000 gCO_2-eq./ 10 000 MJ ethanol. After changing to economic based allocations, only 1% of the fossil energy use and GHG emissions produced were allocated to fungal biomass co-product, which resulted in the total well-to-pump GHG emissions of 140 500 gCO_2-eq./10 000 MJ ethanol.

E. Discussion

Life-cycle assessment of green and dry processing of banagrass-derived ethanol highlights important insights regarding energy use and GHG emissions associated with this tropical grass-to-ethanol option. The analysis has identified some of the key "hot-spots" of energy use and emissions, while also suggesting how energy and green-house gas impacts may be mitigated with improved technological development.

Although green-processing technology to convert high moisture biomass into ethanol has an advantage of co-production generation, the energy use and GHG emissions were found to be higher than those associated with dry processing technology. This is largely due to fungal

cultivation being a relatively energy-intensive process when compared to conventional animal/fish feed sources such as soybean meal. Fungal cultivation is a continuous process requiring sufficient aeration, agitation, and temperature—all of which requires additional energy use. Current animal/fish feed ingredients such as soybean meal themselves are often co-products generated from existing food manufacturing processes (e.g., soybean oil processing), and agrochemical and fuel use during crop production are generally less energy intensive than those used during biochemical manufacturing. Therefore, in order for green-processed technologies to reap fossil energy and greenhouse gas benefits, further research is needed to increase efficiency by improving fungal yield and energy use (e.g., fungal growth options without extensive aeration) and by exploring possibilities to integrate more renewable energy options into processing, such as solar hot-water and industrial steam generation. This will likely involve a trade-off between higher capital investment required for these renewable options vs. gains made in reducing costs and life-cycle emissions, which merits further examination from a life-cycle perspective.

Both green and dry processing of banagrass to E85 ethanol lead to small gains (10 g, 30 g, and 40 g of gCO$_2$-eq./km driven for green processing with co-product, green processing without co-product and dry processing, respectively, as compared to gasoline) according to the well-to-wheel analysis. Continued improvement in technological options and life-cycle GHG footprints of inputs used in the process will lead to further reduction potential. The island of Hawaii currently supplies around 69% of electricity needs by petroleum-based generation facilities, leading to both a high GHG emissions footprint and operational cost of power consumption. The high emissions intensity of power generation reflects unfavorably when a plant is a net consumer of power (as is the case based on parameters chosen in this study); however, the same condition could work favorably when a plant becomes a net producer of energy and additional co-product credit maybe given, in addition to a further stream of revenue generated by electricity sale.

Varying parametric assumptions such as emission factors, enzyme loading, and process power generation effects LCA results considerably, and further optimization of processing conditions will likely reduce chemical and energy usage. As illustrated in sensitivity analysis, existing estimates on energy use and GHG emissions related to enzymes vary widely from 2260 gCO$_2$-eq. per kg of enzyme as reported by MacLean and Spatari (2009) and 8000 gCO$_2$-eq./kg of enzyme as reported by Novozyme (2012). The required enzyme loading to achieve hydrolysis at commercial scale also remains debated; therefore, it is generally difficult to draw robust conclusions regarding GHG benefits of lignocellulosic bioethanol.

Finally, the use of biomass as a source of drying heat, assumed in this study, should be evaluated with caution as biomass drying needs are high especially for dry processing option. To produce 10 000 MJ of ethanol under dry processing, it is estimated that 1.6 dry tons of biomass will be needed for processing. Assuming that biomass has an initial moisture content of around 67%, it is estimated that around 0.50 dry tons of biomass would be needed to bring down the moisture content to 7% assuming biomass boiler efficiency of 75%. If it is technically and economically unfeasible to harvest additional biomass for drying usages, the use of fossil fuel alternative will cause a sharp rise in emissions. Assuming the use of diesel for biomass drying under the same boiler efficiency, it will require approximately 280 l of diesel to dry biomass sufficiently to produce 10 000 MJ of ethanol under dry processing. Such fossil fuel use is likely be unacceptably high on the grounds of both environmental and economic costs. Therefore, if collection of sufficient biomass seems unfeasible due to local resources availability, the adoption of green-processing technology, which eliminates excessive feedstock drying process, could become more favorable, especially in the tropical regions. In this study, the amount of biomass needed to dry fungal co-product was estimated at around 8.5 kg per functional unit of ethanol produced.

V. CONCLUSIONS

This study conducted well-to-pump and well-to-wheel life-cycle GHG assessments of banagrass-to-ethanol options, comparing the innovative concept of green-processing and

conventional dry processing. The well-to-pump analysis show that ethanol production consume 8200 MJ (green processing with co-product), 7600 MJ (green-processing without co-product), and 7200 MJ (dry-processing without co-product) of fossil fuel energy and emit approximately 144 kgCO_2-eq., 90.6 kgCO_2-eq., and 59.1 kgCO_2-eq. per 10 000 MJ of ethanol produced. Well-to-wheel analysis showed that life-cycle GHG emissions per km of FFV driven were 280 g of gCO_2-eq. (green processing with co-product,) 260 gCO_2-eq. (green processing without co-product), and 250 gCO_2-eq. (dry processing without co-product).

Green-processing with the novel co-product generation option was found to require more fossil energy consumption, thus produce more emissions due to additional energy needed for fungal growth and related processes. One of the caveats identified in this analysis is that green-processing may still be the preferred option under tropical climates, if prior feedstock drying needed for conventional processing using a biomass-fired plant proves to be unfeasible due to economic reasons. Based on the current level of technologies determined mostly by lab scale observations, GHG emissions reduction potential of both green and dry processing options as compared with conventional gasoline appears limited.

ACKNOWLEDGMENTS

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