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Assessing multimetric aspects of sustainability: Application to a bioenergy crop production system in East Tennessee

Esther S. Parish,[1,†] Virginia H. Dale,[1] Burton C. English,[2] Samuel W. Jackson,[3] and Donald D. Tyler[4]

[1]*Center for BioEnergy Sustainability, Environmental Sciences Division, Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831 USA*
[2]*Agricultural and Resource Economics Department, The University of Tennessee Institute of Agriculture, 2621 Morgan Circle, Knoxville, Tennessee 37996 USA*
[3]*Genera Energy Inc., 167 Tellico Port Road, Vonore, Tennessee 37885 USA*
[4]*University of Tennessee West Tennessee Research and Education Station, 605 Airways Boulevard, Jackson, Tennessee 38301 USA*

Citation: Parish, E. S., V. H. Dale, B. C. English, S. W. Jackson, and D. D. Tyler. 2016. Assessing multimetric aspects of sustainability: Application to a bioenergy crop production system in East Tennessee. Ecosphere 7(2):e01206. 10.1002/ecs2.1206

Abstract. This article connects the science of sustainability theory with applied aspects of sustainability deployment. A suite of 35 sustainability indicators spanning 12 environmental and socioeconomic categories has been proposed for comparing the sustainability of bioenergy production systems across different feedstock types and locations. Information on sustainability indicators and associated measurements for the feedstock production and logistics portions of the biofuel supply chain was available from a recent demonstration-scale switchgrass-to-ethanol production system located in East Tennessee. Knowledge pertaining to the available indicators was distributed within a hierarchical decision tree framework to generate an assessment of the overall sustainability of this no-till switchgrass production system relative to two alternative business-as-usual scenarios of unmanaged pasture and tilled corn production. The relative contributions of the social, economic, and environmental information were determined for the overall trajectory of this bioenergy system's sustainability under each scenario. The results show that, within this East Tennessee context, switchgrass production is an attractive option for improving environmental and social sustainability trajectories without adverse economic impacts, which can lead to enhanced sustainability overall. Although external trade does not yet exist for this switchgrass commodity, our economic modeling indicates that switchgrass production can still be beneficial to the counties surrounding the biorefinery in terms of dollars earned and jobs created. The opportunity to use inactive equipment and laborers is a potential benefit captured indirectly by the sustainability evaluation framework. Given the early stage of cellulosic ethanol production, it is currently difficult to determine quantitative values for all 35 proposed sustainability indicators across the entire biofuel supply chain. This case study demonstrates that integration of qualitative sustainability indicator ratings may increase holistic understanding of a bioenergy system in the absence of complete information.

Key words: bioenergy crop; biofuel; cellulosic ethanol; decision support; indicators; multimetric; *Panicum virgatum*; scale; sustainability; switchgrass; Tennessee.

Received: 10 March 2015; revised 13 May 2015; accepted 19 May 2015. Corresponding Editor: D. P. C. Peters.
This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S.

† **E-mail:** parishes@ornl.gov
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Introduction

The concept of sustainability underlies conservation, mitigation, restoration, and pro-active protection of the environment. Consideration of the sustainability of Earth's resources becomes quite heated when energy is discussed. This debate is occurring because all forms of energy extraction and use have some negative consequences, and because energy availability underlies much of human development and advances in health, wealth, food security, and stability (Martinez and Ebenhack 2008, Dale and Ong 2012). Although sustainability is still an imprecisely defined concept, numerous polices call for its implementation. The science underlying sustainability must be clear in order to use its tenets, and sustainability assessments must be demonstrated and validated within real-world agricultural systems in order to understand potential ecological tradeoffs (Robertson and Swinton 2005). This article connects the science of sustainability theory with applied aspects of sustainable deployment of bioenergy production systems.

The U.S. government and its agencies, including the Department of Energy (DOE), are seeking ways to move toward sustainable forms of energy. U.S. Federal Executive Order (E.O.) 13514, "Federal Leadership in Environmental, Energy and Economic Performance," defines "sustainability" as the creation and maintenance of conditions "under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations." As biofuels production ramps up to meet the requirements of the U.S. Energy Security and Independence Act of 2007, it is critical to develop an integrated strategy for implementation that addresses sustainability concerns in view of multiple constraints and objectives, including land management practices, energy pressures, economic constraints, social context, and changing climate conditions.

Sustainability assessment and implementation of policy to support it necessitate the translation of sustainability principles and criteria into "indicators," meaning measurements intended to provide critical information about the effects of human activities on environmental, social, and economic conditions over time. Multiple global and national agencies have proposed indicators to assist in the assessment of progress toward sustainable bioenergy production practices, but these indicator lists have tended to be lengthy, burdensome, and lacking in information about specific measurements. A comparatively simple suite of 35 indicators within six environmental categories (McBride et al. 2011) and six socioeconomic categories (Dale et al. 2013) has been developed for assessing the sustainability of biofuel production pathways (Fig. 1). While these indicators are intended to apply to a wide variety of bioenergy systems, sustainability goals are inherently place-based and subject to the context of particular locations and feedstocks (Dale et al. 2013, Efroymson et al. 2013, Florin et al. 2014). Field testing of the proposed indicator suite within a variety of bioenergy systems is needed to ensure adoption by the biofuels industry (McBride et al. 2011). An effective method of integrating collected socioeconomic and environmental indicators is also needed for holistic understanding of a bioenergy system's sustainability "trajectory," meaning its progress toward (or away from) sustainability targets (Florin et al. 2014).

This case study explores practical aspects of sustainability indicator data collection and integration. A recent demonstration-scale East Tennessee switchgrass-to-ethanol production system is used to examine the availability and interpretation of sustainability indicator data for the feedstock production and logistics portions of a biofuel supply chain (Fig. 1). Context-specific indicator information is aggregated within a hierarchical decision tree framework to generate an assessment of the overall sustainability of this no-till switchgrass (*Panicum virgatum*) production system relative to two alternative business-as-usual scenarios of unmanaged pasture and tilled corn production. Finally, the relative contributions of the social, economic, and environmental information to the local agricultural system's sustainability trajectory under each alternative scenario are considered. Through this case study analysis, we attempt to answer the following questions: Is it possible to assess a bioenergy system's overall sustainability trajectory by integrating multimetric information gathered from across a variety of spatial and temporal scales? Do some sustainability indicators contribute more to the overall sustainability determination

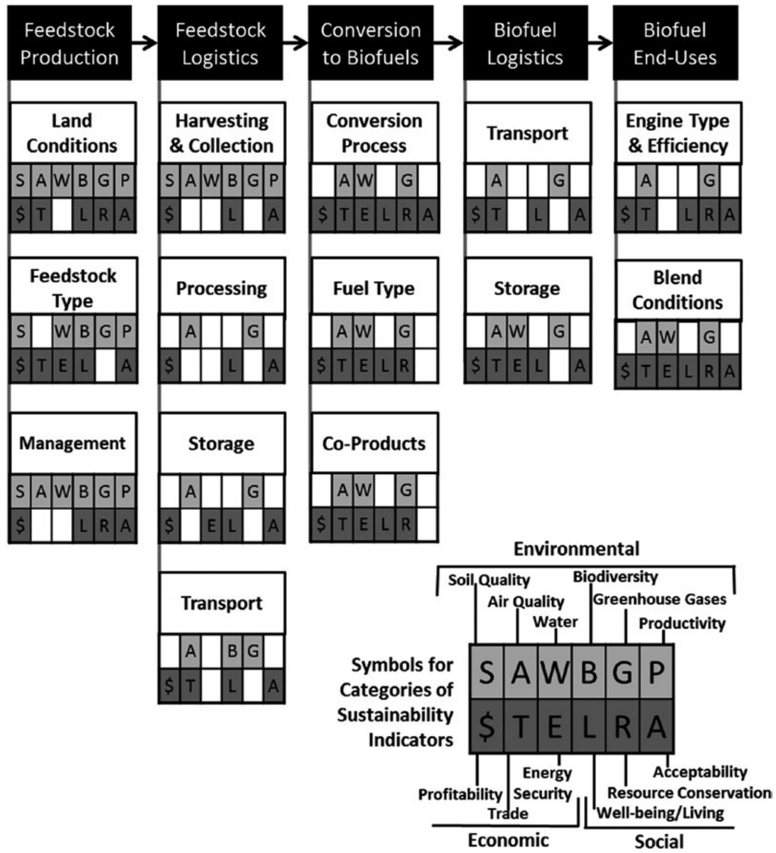

Fig. 1. Applicability of recommended environmental, economic, and social sustainability indicator categories across the biofuel supply chain (Dale et al. 2013, Efroymson et al. 2013). For the East Tennessee switchgrass-to-ethanol case study, all 12 categories of indicator data were assessed for the feedstock production and feedstock logistics steps of the biofuel supply chain.

than others? If so, how context-specific is this influence? The paper concludes with a discussion of the case study assessment limits and recommendations for future research.

Background

This sustainability evaluation focuses on a demonstration-scale switchgrass-to-ethanol experiment located within an 11-county area of East Tennessee found in the Southeastern United States (Fig. 2). From 2007 to 2012, the Tennessee Biofuels Initiative invested $70.5 million in the construction of a pilot-scale biorefinery designed to produce cellulosic ethanol from switchgrass plantings that were simultaneously established throughout surrounding counties (Tiller 2011). The dedicated cellulosic ethanol experiment was designed to examine actual yields and production costs of a dedicated bioenergy feedstock under a wide range of physical settings and realistic farm management conditions, as well as to demonstrate the willingness and ability of Tennessee producers to grow switchgrass under contract (Clark et al. 2007). The Vonore, Tennessee, biorefinery, currently operated by DuPont Cellulosic Ethanol, opened in 2010 with the capacity to produce approximately 1 million L (250 000 gal) of ethanol per year from corn cobs, corn stover, switchgrass and other biomass sources. The cellulosic transportation fuel produced by this Vonore biorefinery has been utilized as E-85 fuel in the University of Tennessee Motor Pool fleet.

The Vonore biorefinery was constructed within the preexisting Monroe County Niles Ferry

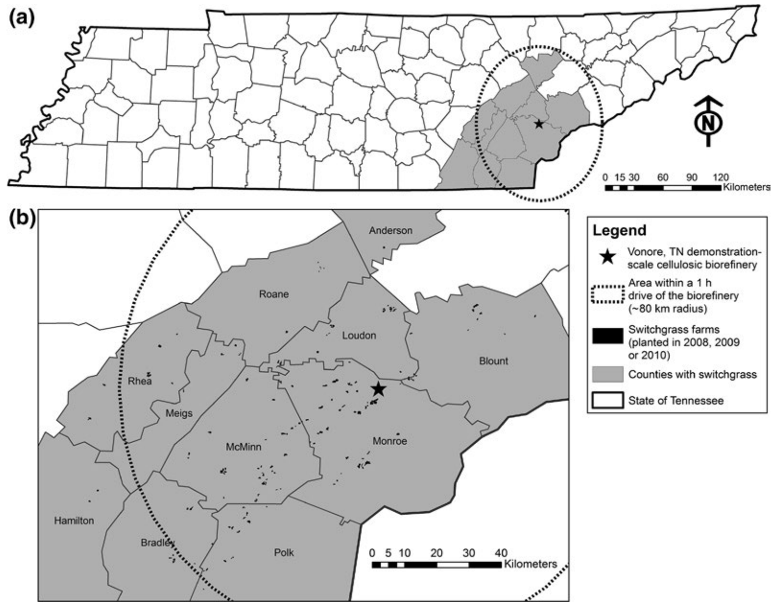

Fig. 2. (a) Location of the East Tennessee switchgrass-to-ethanol experiment within the Southeastern United States. Applications for feedstock contracts were considered from Tennessee farms located within 80 km (50 miles), i.e., approximately a 1-h drive, from the Vonore demonstration-scale biorefinery. (b) At the peak of production in 2010, 2064 ha (5100 acres) of switchgrass were distributed throughout 11 East Tennessee counties.

Industrial Park with ready access to barge traffic, highways, and a railway system. Adjacent to the biorefinery, Genera Energy Inc. operates an 8.9 ha (22 acre) Biomass Innovation Park research campus to demonstrate and optimize the feedstock supply chain, including conveying, preprocessing, and storing material, for a variety of cellulosic biomass types, including switchgrass (Tiller 2011).

Simultaneous with the Vonore biorefinery construction beginning in 2007, three rounds of 3-yr contracts to grow switchgrass were offered to East Tennessee farmers within an approximately 1-h drive of the facility (Fig. 2). Therefore, the "fuelshed" for this project, i.e., the total land area considered for providing dedicated biomass, included Tennessee land within an 80-km (50-mile) radius around the Vonore biorefinery and the adjacent Biomass Innovation Park (Fig. 2). At the peak of production in 2010, 2064 ha (5100 acres) of switchgrass were planted across 11 Tennessee counties (Fig. 2), and Tennessee Biofuels Initiative envisioned the potential for expansion to 10 117 ha (25 000 acres) of switchgrass (Velandia et al. 2010). Farmland contracted for the switchgrass plantings consisted of row crops (i.e., soybeans, corn grain, corn silage, and green beans); close grown wheat, and pasture/hay (e.g., fescue, alfalfa, orchard grass), as well as some fallow land previously used for pasture/hay or row crops.

Switchgrass was selected as the dedicated bioenergy crop for this East Tennessee experiment for a variety of reasons. More than 30-yr worth of lab- and field-based studies of switchgrass have shown that this perennial, native plant offers several advantageous qualities, including drought and flood tolerance, high yield capacity with little to no fertilizer application, the ability to stabilize soils and sequester carbon with long root systems, and the potential to improve water quality (McLaughlin and Walsh 1998, Tolbert et al. 2002, Dale et al. 2011). Switchgrass has a lifespan of at least 20 yr with high yields following the third year after establishment. It is neither rhizomatous nor invasive (Lewis and Porter 2014). A socioeconomic advantage of switchgrass as a bioenergy crop within this context is the fact that it can be planted and harvested with equipment already available to East Tennessee farmers. Switchgrass can provide animal forage concomitant with bioenergy production and has the potential to improve wildlife habitat for declining grassland bird populations (Tiller 2011). The lowland variety of switchgrass, Alamo, was selected for this experiment due to its high yields and suitability for a southern climate.

University of Tennessee Institute of Agriculture (UTIA) Extension Agents worked closely with the selected Vonore-area farmers to teach them how to manage this crop of native warm-season perennial grass. Experience showed that switchgrass was most easily established on land formerly controlled for weeds (i.e., land formerly used for row crops), but that high switchgrass yields of 13–18 MT/ha (6–8 U.S. tons/acre) could also be successfully obtained from low productivity lands with very poor soil quality or steep slopes (e.g., land that was fallowed and entering the early stages of succession). High yields on low productivity land did not necessarily translate to commercially harvestable switchgrass, however, and it was learned that the field configuration and size were also key factors in the overall production process (C. Clark, *personal communication*).

The Vonore, Tennessee, switchgrass-to-ethanol experiment provides a unique opportunity to examine a variety of environmental and socioeconomic data needed to analyze the overall sustainability of a dedicated bioenergy crop production system. Several recently completed studies, both published and unpublished, pertain to the 12 recommended categories of sustainability indicators, including: social acceptability surveys (Qualls et al. 2012); analyses of crop yields and soil quality at the farm and field scale; analyses of water quality and quantity from several catchments containing different proportions of switchgrass; a life-cycle inventory of greenhouse gases and water emissions associated with cradle-to-grave switchgrass pellet production (Reed 2012); an analysis of bird preferences (West 2011); and several economic models of transportation, storage, and conversion processes (e.g., English et al. 2013).

Methods

For this sustainability assessment of the 5-yr, 2023 ha (5000 acre), East Tennessee switchgrass-to-ethanol experiment (Fig. 2), we limit our analysis to the feedstock production and logistics portions of the supply chain (i.e., field-to-biorefinery gate; Fig. 1) for which a variety of data are available. We evaluate the bioenergy production system's sustainability relative to two alternative business-as-usual 5-yr agricultural production scenarios representative of the upper and lower bounds of local agricultural management practices: 2023 ha (5000 acres) of tilled corn production and 2023 ha (5000 acres) of unmanaged pasture. The key similarities and differences between the three scenarios are shown in Table 1. For clarification, no irrigation is used for agricultural production in East Tennessee, and there is more than enough land available for the number of cows grazing in the region. Steep land and areas of poor soil make corn grain yields much lower in East Tennessee than other parts of the United States (e.g., the Midwest), as demonstrated by the fact that average annual corn grain yields for this region have been as much as 50% lower than the U.S. national average over the past 15 yr (Appendix S1).

We compare the three alternative scenarios (Table 1) within a qualitative sustainability evaluation framework built for our case study using freely available DEXi 4.0 software. DEXi is designed to solve complex decision problems that involve 15 or more attributes, inaccurate and/or missing data, group decision-making, and expert judgment (which often requires qualitative reasoning rather than numerical evaluation) (Bohanec et al. 2013). Conceptually, DEXi combines "classical" numerical multicriteria decision modeling with rule-based expert systems, presenting the user with words rather than numbers and employing a tabular representation of utility relations designed to facilitate discussion and group decision-making (Bohanec et al. 2013). DEXi allows the evaluation of multiple options by decomposing the decision problem into more easily solved subproblems. This decomposition is done by creating a hierarchical decision tree with attributes and ratings (called "scales" by the software) attached to each branch. Versions of DEXi have been used successfully to integrate both quantitative and qualitative environmental, social, and economic information about proposed innovative agricultural systems and agricultural management techniques (Bohanec et al. 2008, Pelzer et al. 2012, Vasileiadis et al. 2013). Hereafter, the DEXi evaluation tool is referred to as a Multi-Attribute Decision Support System (MADSS).

Table 1. Three scenarios used to evaluate the sustainability of an East Tennessee dedicated switchgrass-to-ethanol production system.

Assumptions	No-till switchgrass	Tilled corn	Unmanaged pasture
Total production area	2023 ha (5000 acres)	2023 ha (5000 acres)	2023 ha (5000 acres)
Time span of production	5 yr	5 yr	5 yr
Time of planting	Planted once in spring (no replanting required for at least 10 yr)	Planted annually	No planting (previously established)
Planting method	No-till method with a drill	Planted conventionally into a prepared seedbed	None
Harvesting equipment	Conventional hay equipment	Combine	Harvested by cows with a carrying capacity of 0.61 ha (1.5 acres) per cow
Harvest frequency	Once per year, after November 1st (or the first killing frost)	Once per year, in October	Continuous
Storage	Round bales, tarped	Trucked off farm	None
Herbicide application	One to three applications of glyphosate herbicide prior to planting (with more applications required for land under conversion from pasture/hay). No additional herbicides after planting. Vonore farmers applied an average of 0.045 kg (0.10 lbs) of herbicide per ton of switchgrass produced (Reed 2012)	Annual application of glyphosate herbicide	No herbicide used
Fertilizer application	For soil OP rate of "low," annual (Spring) application is 44 kg/ha (40 lbs/acre) of phosphate (P_2O_5). No P is applied if soil P rating is "medium" or "high." If soil potassium (K) test is "low," 88 kg/ha (80 lbs/acre) of potash (K_2O) is applied. No K is applied if soil K rating is "medium" or "high". After the first year, an annual (Spring) application of 66 kg/ha (60 lbs/acre) of nitrogen is suggested (for too much weed competition ensues if it is added during the establishment year). Lime is only added if the soil pH is <5.0	Typical annual application includes 330 kg/ha (300 lbs/acre) of ammonium nitrate (33.5% N), 220 kg/ha (200 lbs/acre) of "10–30–30" and 1100 kg/ha (1000 lbs/acre) of lime, UT Agricultural Extension Service 2001	No fertilizer used
Typical yield	4.5 MT/ha (2 tons/acre) in Year 1, 11 MT/ha (5 tons/acre) in Year 2, and 13–18 MT/ha (6–8 tons/acre) in Years 3–5	7187 kg/ha (114.5 bushels/acre) of corn averaged over 2007–2013	Pasture Roughage = 4.7 MT/ha (2.1 tons/acre) estimated as mixed hay
Price information	Estimated price Actual contract price of $1112/ha ($450/acre) Estimated delivered price of $78.52/MT ($71.23/ton) assuming $3.58/MT ($3.25/ton) storage cost	Estimated price East TN average for 2007–2013 = $5.04/bushel	Estimated pasture price assumed to equal hay price East TN average for 2007–2013 = $90.79/ton
Final destination	189 million L/yr (50 million gallon/yr) Biorefinery within a 1-h drive with conversion rate of 18 MT per liter (76 tons per gallon) of ethanol produced	Multiple uses including silage for animal feed, corn syrup, direct human consumption, and ethanol production	On-site cattle roughage

Note: The 2023 ha (5000 acres) of agricultural production considered under each scenario are assumed to be distributed throughout the 11-county area depicted in Fig. 2. These assumptions were used in the economic modeling described in Appendix S3.

To build the MADDS for our case study, we first placed the overall "sustainability" rating that influences decisions regarding management changes at the top of the decision tree (with possible values of "high sustainability," "intermediate sustainability," and "low sustainability") supported by the three "pillars" of environmental, economic, and social sustainability and multiple subbranches extending below each of these three sustainability pillars (Fig. 3). We incorporated

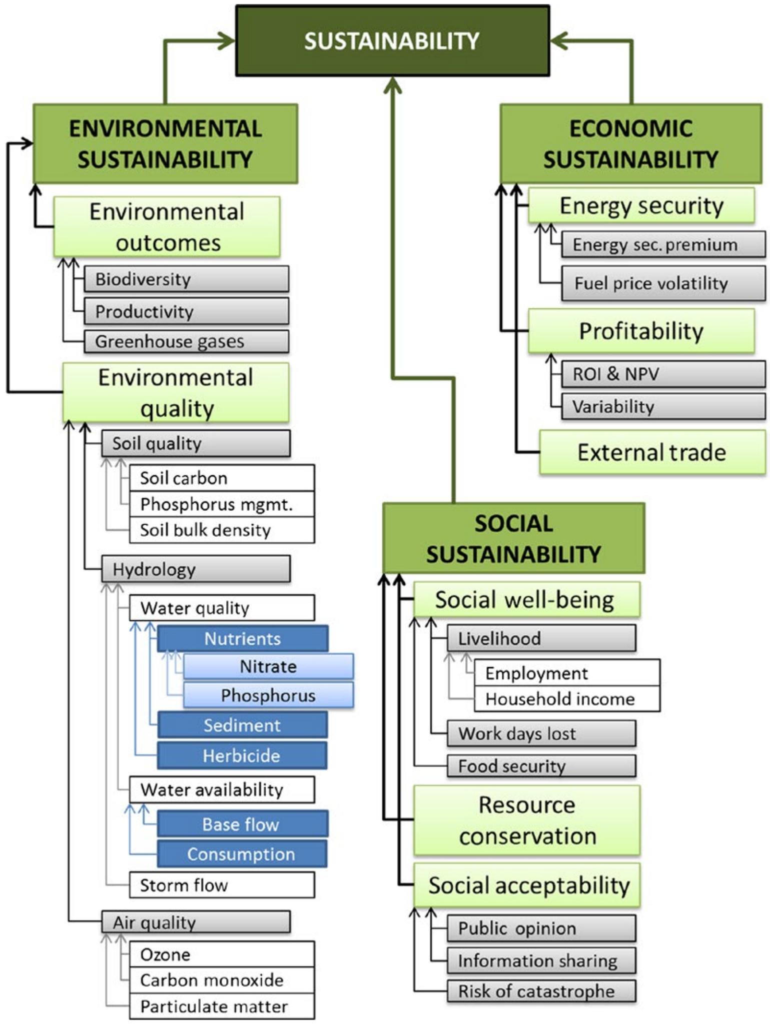

Fig. 3. Aggregation hierarchy of 12 categories of sustainability indicators within a Multiattribute Decision Support System (MADSS) model constructed to evaluate the overall progress toward sustainability of a bioenergy system. The "sustainability" determination for the field-to-biorefinery gate portion of this East Tennessee switchgrass-to-ethanol experiment was based on a combination of environmental, economic, and social indicators of bioenergy sustainability proposed by McBride et al. (2011) and Dale et al. (2013).

context-specific information pertaining to six categories of environmental indicators (Table 2) and six categories of socioeconomic indicators (Table 3) within the hierarchical aggregation framework so that we could use our MADSS to explore the sustainability trajectory of the case study bioenergy production system relative to the two local alternatives for agricultural production (Table 1).

Models built with DEXi software are most stable when there are no more than three variables used at each level of the aggregation hierarchy. Therefore, prior to the indicator data collection and analysis (see Appendices B and C), we made decisions about aggregation of the sustainability indicators at several levels of the MADSS decision tree. First, we divided the six categories of recommended environmental sustainability indicators (McBride et al. 2011) into two groups: (1) "Environmental Quality" indicators related to air quality, soil quality, and water quality and quantity, and (2) "Environmental Outcomes" environmental indicators related to greenhouse gas emissions, biodiversity, and aboveground

Table 2. Environmental sustainability indicator ratings assigned to the feedstock and logistics portions of an East Tennessee switchgrass-to-ethanol demonstration-scale production system.

Sustainability indicator category	Sustainability indicator	Case study information	Sustainability ratings		
			Low	Intermediate	High
Soil quality	Total organic carbon (TOC) in Mg/ha	38 Mg/ha at depth of 15–20 cm (6–8 in.) after 3 yr of production (n = 120) with increasing trend	Decreasing soil TOC over years	No change in soil TOC	**Increasing soil TOC over years**
	Total nitrogen (N) in Mg/ha	…	…	…	…
	Extractable phosphorus (P) in Mg/ha	0–0.06 Mg/ha at depth of 15–20 cm (6–8 in.) averaged over 3 yr (n = 120)	Additions of P exceed removal rate	**P applied at removal rate**	No P applied to soil
	Bulk density in g/cm^3	1.2 g/cm^3 at depth of 15–30 cm (6–12 in.) prior to 2008 plantings (n = 120)	Low bulk density OR high bulk density	**Nonrestrictive bulk density†**	N/A
Water quality and quantity	Nitrate concentration in streams in mg/L and as export in kg·ha^{-1}·yr^{-1}	Export of 0.36 kg·ha^{-1}·yr^{-1} measured at Thompson farm; 0.15 mg/L modeled in Lenoir City catchment	Increasing nitrate concentration/export over years	No change in nitrate concentration	**Decreasing nitrate concentrations/export over years**
	Total phosphorus (P) concentration in streams as mg/L and as export in kg·ha^{-1}·yr^{-1}	Export of 0.13 kg·ha^{-1}·yr^{-1} measured at Thompson farm; 0.11 mg/L modeled in Lenoir City catchment	Increasing P concentration/export	No change in P concentration/export	**Decreasing P concentration/export**
	Suspended sediment concentration in streams as mg/L and as export in kg·ha^{-1}·yr^{-1}	Export of 0.86 kg·ha^{-1}·yr^{-1} measured at Thompson farm; 66 mg/L modeled in Lenoir City catchment	Increasing sediment concentration	No change in sediment concentration	**Decreasing sediment concentration**
	Herbicide concentration in streams as mg/L and export in kg·ha^{-1}·yr^{-1}	~1406 kg (one-time total) of glyphosate applied to 2023 ha of production spread across an 11-county area	Multiple herbicide applications	**Herbicide only applied during establishment phase**	No herbicide applications
	Peak storm flow in L/s	6769 L/s measured at Notchy Creek; extremely low C factor measured at Thompson farm	Increased potential for flash flooding	Expected storm runoff behavior	**Improved capacity to absorb excess water**
	Minimum base flow in L/s	203 L/s measured at Notchy Creek	Decreasing base flow	**No change in base flow**	Increasing base flow
	Consumptive water use (incorporates base flow) as m^3·ha^{-1}·d^{-1}	No irrigation used; highly efficient plant photosynthesis and transpiration by Alamo switchgrass	Inefficient water use	Normal water use	**Highly efficient water use**
Air quality	Tropospheric ozone in ppb	Reduced use of heavy field equipment for perennial crop	Higher ozone emissions	Average ozone emissions	**Lower ozone emissions**
	Carbon monoxide in ppm	Reduced use of heavy field equipment for perennial crop	Higher CO emissions	Average CO emissions	**Lower CO emissions**
	Total particulate matter <2.5 m diameter ($PM_{2.5}$) in μg/m^3	0.209 MT/yr (combined field operations, transportation and handling)	Higher PM emissions	Average PM emissions	**Lower PM emissions**
	Total particulate matter <10 m diameter (PM_{10}) in μg/m^3	0.037 MT/yr (combined field operations, transportation and handling)			

Table 2. Continued.

Sustainability indicator category	Sustainability indicator	Case study information	Sustainability ratings		
			Low	Intermediate	High
Productivity	Aboveground net primary productivity (ANPP)/yield in g $C \cdot m^{-2} \cdot yr^{-1}$	394.5 g $C \cdot m^{-2} \cdot yr^{-1}$ for mature switchgrass with a yield of 13–18 MT/ha (6–8 tons/acre) per year	Low productivity	Average productivity	**High productivity**
Biodiversity	Presence of taxa of special concern	Observed increase in quail	Less biodiversity	Same biodiversity	**More biodiversity**
	Habitat area of taxa of special concern in ha	No information available			
Greenhouse gases (GHGs)	CO_2 equivalent (CO_2 and N_20) in kg Ceq/GJ emissions	334.65 tons/yr CO_2 emissions (178.75 tons from growth and harvesting operations, 103.7 tons from electricity and diesel used by Genera's handling facility, and 52.2 tons from transportation logistics)	More GHG emissions	**Some GHG emissions**	Fewer GHG emissions

Notes: A total of 19 environmental sustainability indicators in six categories were considered (McBride et al. 2011). The potential sustainability ratings were used within the multiattribute decision support system (MADSS) to compare the environmental sustainability of no-till switchgrass production to alternative scenarios of tilled corn and unmanaged pasture (Table 1). The qualitative ratings assigned to the no-till switchgrass scenario are shown in bold font. Ellipses were used to indicate "no data." A cell value of "N/A" was used to indicate that the rating category did not apply to the particular indicator. Sources and assumptions used to generate these socioeconomic indicator ratings are discussed in Appendix S2.

† Within this East Tennessee context, nonrestrictive bulk soil density is defined as 1.35-1.5 g/cm3.

Table 3. Socioeconomic sustainability indicator ratings assigned to the feedstock and logistics portions of an East Tennessee switchgrass-to-ethanol demonstration-scale production system.

Sustainability indicator category	Sustainability indicator	Case study information	Sustainability ratings		
			Low	Intermediate	High
Social well-being	Employment as # of full-time equivalent jobs	67–96 jobs created within the 13 counties surrounding the biorefinery	Fewer jobs	No change in jobs	**More jobs**
	Household income as \$/d	Income from harvesting switchgrass will be additional as November harvest occurs at a time when there is no other local agricultural work available	Less household income	Same household income	**More household income**
	Work days lost due to injury as average # work days lost per worker per year	Genera had recorded 0 incidents for switchgrass harvesting and preprocessing operations for over 1325 d	Increase in work days lost	**Average work days lost**	Decrease in work days lost
	Food security as % change in food price volatility	No observed changes in food price volatility	Increasing food price volatility	**No noticeable change in food price volatility**	Decreasing food price volatility
Resource conservation	Depletion of nonrenewable energy resources as amount of petroleum extracted per year (MT)	Over 2 million gallons of gasoline replaced by local ethanol (annually), keeping \$5.1–\$5.8 M in the region	Net increase in fossil fuel consumption	N/A	**Net decrease in fossil fuel consumption**
	Fossil energy return on investment (fossil EROI) as ratio of amount of fossil energy inputs to amount of useful energy output (MJ) (adjusted for energy quality)	EROI = 5.44 (per Wang et al. 2012, national assessment)			

Table 3. Continued.

Sustainability indicator category	Sustainability indicator	Case study information	Sustainability ratings: Low	Intermediate	High
Social acceptability	Public opinion as percent favorable opinion	55% of TN farmers responded favorably in 2009 to growing switchgrass and 87% of Vonore switchgrass producers were willing to continue in 2010	Negative public opinion	Neutral public opinion	**Positive public opinion**
	Transparency as percent of indicators for which timely and relevant performance data are reported	Stakeholder participation in this experiment was 100% as all switchgrass producers were required to meet with Extension agents and there were a variety of surveys, public meetings and focus groups	Low stakeholder engagement	Average stakeholder engagement	**High stakeholder engagement**
	Effective stakeholder participation as percent of documented responses addressing stakeholder concerns and suggestions (reported on an annual basis)				
	Risk of catastrophe as annual probability of catastrophic event	1 arson event in 5 yr that affected 22% of biorefinery's annual production capacity (i.e., 56 000 gallons lost)	Increased risk	Average risk	**Reduced risk**
Energy security	Energy security premium in $/gal of biofuel	Domestic production increases U.S. energy security	High energy security premium	Neutral energy security premium	**Low energy security premium**
	Fuel price volatility as standard deviation of monthly percent price changes over 1 yr	Local production decreases fuel price fluctuation	Increased fuel price volatility	No change in fuel price volatility	**Decreased fuel price volatility**
External trade	Terms of trade as price of exports/price of imports	$0	**Low external trade**	Some external trade	High external trade
	Trade volume in dollars (net exports or balance of payments)	$0			
Profitability	Return on investment (ROI) as a percent based on net investment/initial investment	Direct economic impact of $2 719 000 and total economic impact of $5 205 000; net profit of $230/ha within 25 yr (Bansal et al. 2013)	Low returns	**Average returns**	High returns
	Net present value (NPV) in dollars (present value of benefits minus present value of costs)				
	Profit variability†	Switchgrass yields and prices were unaffected by weather events, pests, or external market conditions	Highly variable profit	N/A	**Low profit variability**

Notes: A total of 16 socioeconomic sustainability indicators in six categories were considered (Dale et al. 2013), but some were combined for qualitative rating purposes (e.g., ROI and NPV). The potential sustainability ratings were used within the multiattribute decision support system (MADSS) to compare the socioeconomic sustainability of no-till switchgrass production to alternative scenarios of tilled corn and unmanaged pasture (Table 1). The qualitative ratings assigned to the no-till switchgrass scenario are shown in bold font. A cell value of "N/A" was used to indicate that the rating category did not apply to the particular indicator. Sources and assumptions used to generate these socioeconomic indicator ratings are discussed in Appendix S2.

† This indicator was not included in the list of 16 socioeconomic indicators proposed by Dale et al. (2013).

productivity. Within the "Environmental Quality" indicators, we grouped together the water-related indicators as "Hydrology" indicators with subdivisions of "Water Quality" [including nutrients (nitrogen, phosphorus), sediments, and herbicides], "Water Availability" (including base flow and consumption), and "Peak Storm Flow." We combined measurements of suspended particulate matter <2.5 μm and 10 μm as "Particulate Matter" under the "Air Quality" category. Next, we divided the six categories of socioeconomic sustainability indicators (Dale et al. 2013) into two categories: (1) "Social" indicators related to social well-being, social acceptability, and resource conservation, and (2) "Economic" indicators related to energy security, profitability, and external trade. Within the "Social Well-Being" branch of the "Social" category of indicators, we grouped measurements related to employment and household income as "Livelihood." Finally, beneath "Social Acceptability," we grouped indicator measurements of transparency and stakeholder perception as "Information Sharing."

In order to populate the sustainability evaluation framework with indicator values and ratings in the absence of complete information, a modified Delphi process (Clayton 1997, MacMillan and Marshall 2006) was used to achieve a consensus of opinion among the four co-authors, who are all intimately familiar with the Vonore experiment and collectively have a range of expertise spanning agronomy, logistics, agroeconomics, soil science, and ecology. The MADSS served as the tool to organize the discussion, and the completion of the MADSS process signaled the end of the discussion. The lead author served as a facilitator, first meeting with each co-author one-on-one to discuss the potential for quantifying each of the recommended indicators. She then led three round-table discussions over a 5-week period in 2014 during which time the group collectively discussed and modified the sustainability indicator values, scenario parameters, and qualitative ratings within the sustainability evaluation framework using an iterative format. After each meeting, the facilitator provided a summary of the experts' opinions to the group for revisions in light of the collective replies. Each qualitative indicator rating was developed using a combination of empirical data, modeling results, and scientific literature synthesized through expert opinion (see Appendices B and C for details). The scaling (i.e., low, medium, and high ratings) for each available indicator was selected to highlight the differences between the three alternative scenarios (Table 1) within the MADSS evaluation framework, with special consideration given to trends (either observed or expected) in indicator values measured over several years.

The final decisions about which indicators to include/exclude in the MADSS decision tree as well as the determination of qualitative ratings ("scales") and aggregation ("utility") functions for each hierarchical level of the MADSS were also based on a combination of empirical data, modeling results, and literature review synthesized through expert opinion. All of these decisions were specific to our selected case study and alternative scenarios.

The sustainability ratings were generally aggregated to the next (higher) level according to the following decision rules (a.k.a., utility functions):

1) If the indicator ratings were either all positive or mixed positive and intermediate, then the aggregate was assigned a positive value;
2) If the indicator ratings were either all negative or mixed negative and intermediate, then the aggregate was assigned a negative value;
3) If the indicator ratings were mixed positive and negative (and intermediate), then the aggregate was assigned an intermediate value; and
4) If the indicator ratings were all intermediate, then the aggregate was assigned an intermediate value.

These utility functions were set up in order to avoid preferential weighting of any sustainability indicators or categories during aggregation. Indicators were aggregated to the pillar level before making the final overall sustainability determination in order to prevent the larger number of environmental indicators from skewing the assessment results.

The only exception to the general utility function for aggregation occurred for "profitability" within the Economic category of indicators (Table 3). Based on the local context, the team decided to combine the recommended return on investment (ROI) and net present value (NPV) indicators (Dale et al. 2013) into an overall mea-

Table 4. Environmental sustainability ratings of three alternative agricultural scenarios for East Tennessee, as based on a combination of empirical data, modeling results and literature synthesized through expert opinion.

Sustainability categories and underlying indicators	No-till switchgrass	Unmanaged pasture	Tilled corn
Environmental sustainability	**High environmental sustainability**	**High environmental sustainability**	*Low environmental sustainability*
Environmental outcomes	**Improved environmental outcome(s)**	Mixed environmental outcomes	*Negative environmental outcome(s)*
Biodiversity	**More biodiversity**	Some biodiversity	*Less biodiversity*
Productivity	**High productivity**	***Low productivity***	Average productivity
Greenhouse gases (GHGs)	Some GHG emissions	**Fewer GHG emissions**	*More GHG emissions*
Environmental quality	**Improving aspect(s) of environmental quality**	**Improving aspect(s) of environmental quality**	*Declining aspect(s) of environmental quality*
Soil quality	**Improving soil quality**	**Improving soil quality**	*Declining soil quality*
Soil carbon	**Increasing soil carbon**	No change in soil carbon	*Decreasing soil carbon*
Soil phosphorus (P)	P applied at removal rate	**No P applied to soil**	*Additions of P exceed removal rate*
Soil bulk density	Nonrestrictive bulk density	Nonrestrictive bulk density	Nonrestrictive bulk density
Hydrology	**Improving hydrologic conditions**	**Improving hydrologic conditions**	*Declining hydrologic conditions*
Water quality	**Increasing water quality**	**Increasing water quality**	*Decreasing water quality*
Nutrients	**Decreasing nutrient concentrations**	No change in nutrient concentrations	*Increasing nutrient concentrations*
Nitrate	**Decreasing nitrate concentrations/export**	No change in nitrate concentration	*Increasing nitrate concentrations/export*
Phosphorus (P)	**Decreasing P concentrations/ export**	No change in P concentrations/export	*Increasing P concentrations/export*
Sediment	**Decreasing sediment concentrations**	No change in sediment concentrations	*Increasing sediment concentrations*
Herbicide	Herbicide applied during establishment only	**No herbicide applications**	*Frequent herbicide applications*
Water availability	**Increasing water availability**	No change in water availability	No change in water availability
Base flow	No change in base flow	No change in base flow	No change in base flow
Consumptive use	**Highly efficient water use**	Normal water use	Normal water use
Storm flow	**Improved capacity to absorb excess water**	Expected storm runoff behavior	Expected storm runoff behavior
Air quality	**Higher air quality**	**Higher air quality**	Average air quality
Ozone	**Lower ozone emissions**	**Lower ozone emissions**	Average ozone emissions
Carbon monoxide (CO)	**Lower CO emissions**	**Lower CO emissions**	Average CO emissions
Particulate matter (PM)	**Lower PM emissions**	**Lower PM emissions**	Average PM emissions

Notes: Qualitative attribute ratings shown and italicized font relate to high sustainability. Qualitative ratings shown in bold font relate to low sustainability. Qualitative ratings shown in normal font relate to intermediate sustainability.

sure of economic return (high, medium, or low) and to add to this value a new indicator of profit "variability" (high or low) with the idea that more stable income would be better for producers. However, low variability was not considered enough of a positive to turn average or low returns into a highly profitable situation for switchgrass or pasture. And similarly, highly variable profits were not considered enough of a negative to turn the average returns into a low profitability trajectory for corn.

Results

For this case study, the team found enough information to assign qualitative ratings to all 12 of the recommended environmental and socioeconomic sustainability indicator categories and 28 of the 35 recommended individual indicators (McBride et al. 2011, Dale et al. 2013). Environmental sustainability indicator ratings for all three agricultural scenarios are presented in Table 4; social sustainability indicator ratings

Table 5. Social sustainability ratings of three agricultural scenarios for East Tennessee, as based on a combination of empirical data, modeling results and literature synthesized through expert opinion.

Sustainability categories and underlying indicators	No-till switchgrass	Unmanaged pasture	Tilled corn
Social sustainability	**High**	Intermediate	Intermediate
Social well-being	**Improved social well-being**	*Decreased social well-being*	**Improved social well-being**
Livelihood	**Improved livelihoods**	*Decreased livelihoods*	No change in livelihood
Employment	**More jobs**	*Fewer jobs*	No change in # of jobs
Household income	**More household income**	Some household income	Some household income
Work days lost	Average work days lost	Average work days lost	Average work days lost
Food security	No noticeable change in food volatility	No noticeable change in food volatility	**Decreasing food volatility**
Resource conservation	**Net decrease in fossil fuel consumption**	**Net decrease in fossil fuel consumption**	*Net increase in fossil fuel consumption*
Social acceptability	**High social acceptability**	Neutral social acceptability	Neutral social acceptability
Public opinion	**Positive public opinion**	Neutral public opinion	Neutral public opinion
Information sharing	**High stakeholder engagement**	Average stakeholder involvement	Average stakeholder involvement
Risk of catastrophe	**Reduced risk**	Average risk	Average risk

Note: Qualitative attribute ratings shown in italicized font relate to high sustainability. Qualitative ratings shown in bold font relate to low sustainability. Qualitative ratings shown in normal font relate to intermediate sustainability.

Table 6. Economic sustainability ratings of three agricultural scenarios for East Tennessee, as based on a combination of empirical data, modeling results and literature synthesized through expert opinion.

Sustainability categories and underlying indicators	No-till switchgrass	Unmanaged pasture	Tilled corn
Economic sustainability	Intermediate	*Low*	**High**
Energy security	**Improved energy security**	No change in energy security	**Improved energy security**
Energy security premium	**Low energy security premium**	Neutral energy security premium	**Low energy security premium**
Fuel price volatility	**Decreased fuel price volatility**	No change in fuel price volatility	**Decreased fuel price volatility**
Profitability	Average profitability	Mixed profitability measures	Mixed profitability measures
Return on investment and net present value	Average returns	*Low returns*	Average returns
Variability	**Low variability**	**Low variability**	*Highly variable*
External trade	No external trade	No external trade	**High external trade**

Notes: Qualitative attribute ratings shown in italicized font relate to high sustainability. Qualitative ratings shown in bold font relate to low sustainability. Qualitative ratings shown in normal font relate to intermediate sustainability.

are presented in Table 5, and economic sustainability indicator ratings are presented in Table 6. A comparison of the 12 category ratings generated by MADSS for each of the three scenarios is shown in Fig. 4.

The no-till switchgrass production system showed high sustainability ratings for all of the environmental categories except for "greenhouse gases" (Fig. 4), which was intermediate due to the large number of truck trips currently required to transport the bulky biomass from the field to the biorefinery. The unmanaged pasture scenario showed intermediate to high sustainability ratings for all of the environmental categories except for "productivity," which was inherently low due to lack of management. The tilled corn scenario showed low to intermediate sustainability ratings for all of the environmental categories due to the intensive management required to make this nonnative crop profitable.

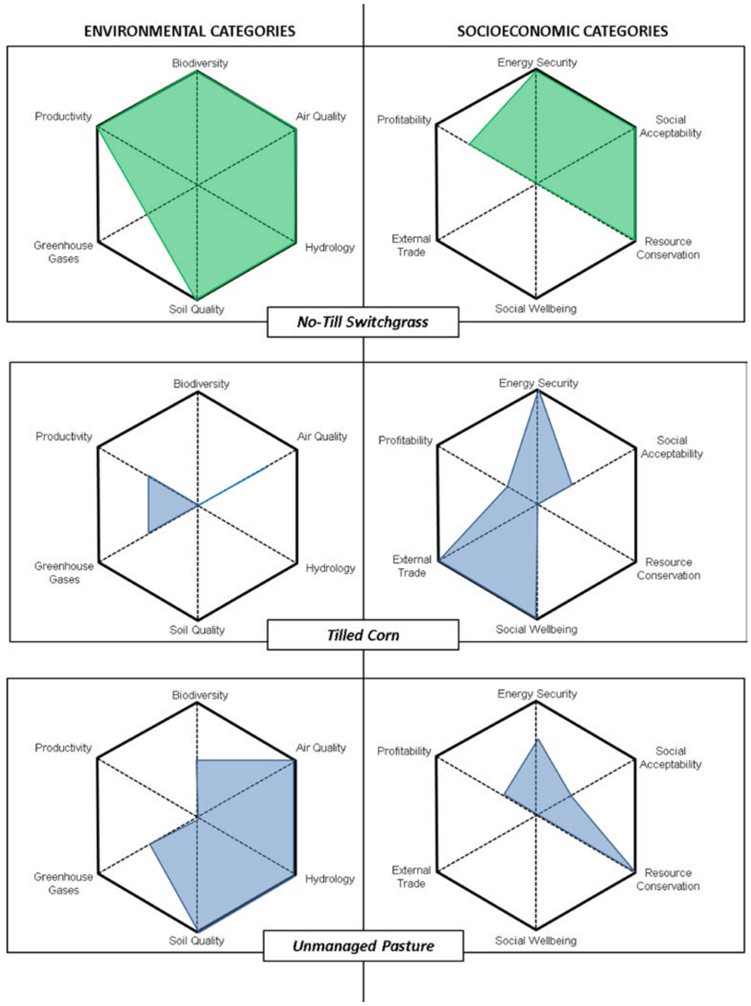

Fig. 4. Ratings of six environmental and six socioeconomic sustainability categories for no-till switchgrass relative to alternative scenarios of tilled corn production and unmanaged pasture. The center points of the hexagons represent lowest possible sustainability ratings, and the outer edges of the hexagons represent highest possible ratings. Thus, larger shaded areas indicate higher sustainability. Each category value represents an aggregation of underlying individual sustainability indicator values.

Table 7. Summary of the overall sustainability and sustainability pillar ratings for the East Tennessee switchgrass-to-ethanol experiment compared to two alternative agricultural scenarios.

Type of sustainability	No-till switchgrass	Unmanaged pasture	Tilled corn
Overall sustainability	High	Intermediate	Intermediate
Environmental sustainability	High	High	Low
Economic sustainability	Intermediate	Low	High
Social sustainability	High	Intermediate	Intermediate

A rollup of the sustainability category ratings (Table 7) shows that no-till switchgrass and unmanaged pasture both achieved "high environmental sustainability" ratings relative to tilled corn's "low environmental sustainability" rating.

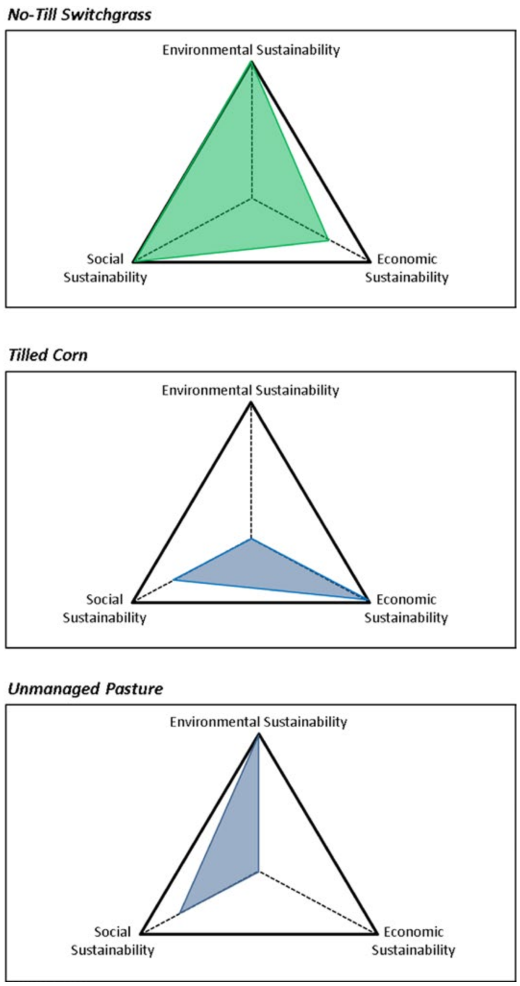

Fig. 5. Relative contributions of the three sustainability "pillars" to the overall sustainability determination for no-till switchgrass (high sustainability) relative to alternative scenarios of tilled corn production (intermediate sustainability), and unmanaged pasture (intermediate sustainability). The center point of each triangle represents the lowest possible sustainability rating, and the outer edges represent the highest possible sustainability rating. Thus, larger shaded areas indicate higher sustainability.

A comparison of the socioeconomic category ratings (Fig. 4) shows that the switchgrass system achieved high sustainability of all three of the social categories and for "energy security" but intermediate sustainability for "profitability," and low sustainability for "external trade" (as there is currently no trade mechanism in place for switchgrass or the locally produced cellulosic ethanol). Corn also achieved high "energy security" due to the fact that some of the locally produced corn is used to make ethanol, but its intense management requirements gave it a low "resource conservation" rating, and its "profitability" and "social acceptability" were intermediate relative to its high ratings for "external trade" and "social well-being." Unmanaged pasture was rated highly for "resource conservation" due to its lack of fossil fuel inputs but rated low to intermediate for the other socioeconomic sustainability categories. Overall, no-till switchgrass showed "high social sustainability" and "intermediate economic sustainability" relative to tilled corn's "high economic sustainability" and "intermediate social sustainability" ratings and unmanaged pasture's "low economic sustainability" and "intermediate social sustainability" ratings (Table 7).

Multiattribute decision support system sustainability determinations for the three pillars of environmental, social, and economic sustainability, as developed with context-specific scaling and utility functions, are summarized in Table 7 and Fig. 5. Overall sustainability determinations for each of the three scenarios were based on underlying qualitative ratings for environmental sustainability indicators (Table 4), social sustainability indicators (Table 5), and economic sustainability indicators (Table 6), which all contributed equally to the highest level of aggregation within the MADSS. The no-till switchgrass scenario achieved a "high sustainability" rating overall based on its underlying "high environmental" and "high social sustainability" ratings in conjunction with an "intermediate economic sustainability" rating. The unmanaged pasture and tilled corn scenarios each received an "intermediate sustainability" rating due to mixed environmental and economic results in conjunction with "intermediate social sustainability" ratings.

Discussion

This sustainability analysis indicates that dedicated switchgrass production for a local biorefinery is an attractive option for East Tennessee with regard to the majority of environmental and socioeconomic aspects of sustainability (Fig. 4). Although external trade does not yet exist for this switchgrass commodity (causing this indicator category to receive the lowest rating of all of the sustainability categories for this scenario), our economic modeling indicates that switchgrass production can still be beneficial to the counties surrounding the biorefinery in terms of dollars earned and jobs created. Once established, annual harvesting of switchgrass can occur at times of the year when farmers are not typically busy preparing or harvesting other crops. This opportunity to make use of otherwise inactive equipment and laborers is a potential benefit captured only indirectly by our sustainability evaluation framework.

At the outset of this analysis, our team's familiarity with the context of this bioenergy system led us to anticipate that profitability and social acceptance (with its ties to local farmer pride in improving national energy security) would be the most critical sustainability indicators for the feedstock and logistics portions of the Vonore switchgrass-to-ethanol experiment. Although the MADSS showed low price variability and improved energy security for no-till switchgrass production, the overall economic sustainability rating was intermediate (Table 7). This rating was due to the strong influences of intermediate price returns and a lack of external trade (Table 6). Corn production showed a positive economic sustainability rating in spite of its high variability and average returns (Table 6). This result derived largely from corn's high trade volume coupled with the fact that some of the corn is also used for ethanol production, thereby helping to achieve energy security. Switchgrass did show a higher economic sustainability than unmanaged pasture, which is a predominant agricultural land use in East Tennessee. The switchgrass scenario was the only scenario to show a positive social sustainability rating (Table 5), as strongly influenced by high levels of stakeholder involvement unique to this demonstration project (i.e., strong leadership by UT Extension Agents, multiple meetings, and surveys).

This case study of switchgrass-to-ethanol production in East Tennessee was unique in several other respects. Switchgrass is native to East Tennessee and has greater potential for consistent profit relative to corn production in the region than other areas of the United States. This was a demonstration project funded by the State of Tennessee. Farmers were given incentives to grow switchgrass while the biorefinery was under construction, thereby ensuring full yields and an adequate supply of switchgrass by the time the biorefinery came on line. The UT Extension Agents worked closely with each switchgrass producer to ensure optimal yields, and each producer was required to collect data throughout the duration of the project. Heavy involvement in the project by UT faculty and students led to the production of a variety of data sets and publications that might not be as readily available in other settings. All of these context-specific factors should be considered when comparing the sustainability assessment of this pilot-scale switchgrass-to-ethanol experiment with other bioenergy systems in other settings.

Limited data availability from commercial-scale and even pilot-scale cellulosic biofuel production systems currently precludes the collection of data pertaining to all 35 of the recommended indicators of sustainability across each relevant step of the biofuel supply chain (Fig. 1). Although we chose to limit our case study analysis to the feedstock production and logistics portions of the supply chain, we lacked sufficient data to conduct a quantitative analysis of sustainability based on the 35 recommended indicators (McBride et al. 2011, Dale et al. 2013). The available data sets varied widely in terms of quality, spatial extent, and length of record, but there was sufficient information to compare sustainability across all 12 of the recommended categories of indicators. It is important to acknowledge the wide range of spatial extents covered by this analysis, including: point-source data related to the biomass processing facility; field-scale analysis of soil quality and fertilizer management regimes as well as harvesting operations; catchment- and watershed-level examination of sediment and nutrient and herbicide runoff; regional-scale analysis of trade volumes and air emissions from an 11-county road network; and national-scale fuel price volatility. In spite of these complicating factors, the use of available data sets (both empirical and modeling based) in combination with local expert knowledge and literature review enabled us to assign qualitative ratings to nearly all of the indicators for aggregation within the hierarchical decision tree framework. Thus, this case study demonstrates that incomplete information does not preclude holistic assessment of a bioenergy system's sustainability.

Sustainability assessments will benefit from indicator measurements repeated over time, and we recommend the periodic incorporation of newly acquired data into sustainability evaluation frameworks such as the MADSS presented here as well as the into management processes. Through the process of adaptive management, i.e., the viewing of policies and system interventions as experiments that need to be continuously monitored, updated, and adjusted (Groot and Rossing 2011), more complete understanding of bioenergy production systems will be gained over time, and it will become possible to assign meaningful targets and weightings to the proposed set of environmental and socioeconomic sustainability indicators. Ultimately, sustainability assessments of a variety of bioenergy feedstocks in diverse settings will be necessary for the development of sound best management practices that sufficiently address the multiple and sometimes competing demands of stakeholders.

Acknowledgments

Funding for this research was provided by the USA Department of Energy (DOE) under the Bioenergy Technologies Office (BETO). Oak Ridge National Laboratory (ORNL) is managed by UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725. Support for this research was also provided by the Southeastern Partnership for Integrated Biomass Supply Systems (IBSS), which is funded through Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30410 from the USDA National Institute of Food and Agriculture. A portion of the soil data was provided by Nicolé Labbe from work supported by the USDA/DOE Biomass Research and Development Initiative under contract EE0002993. Thank you to our DOE BETO sponsor, Kristen Johnson, for her support of this project. Thanks to Latha Baskaran of ORNL for her analysis of hydrologic data provided by Zachariah Seiden and John Schwartz of The University of Tennessee (UT). Thanks to Jamey Menard of the UT Institute of Agriculture (UTIA) for conducting economic analysis of our case study and alternative scenarios. Thanks to Jessica McCord, Chris Clark, and Edward Yu of UTIA, Jesse Daystar of North Carolina State University, and other IBSS collaborators for the providing their manuscripts and clarification. Thanks to Gina Busby of ORNL for cross-checking references. And last, but not least, thanks to Nathan Pollesch of UT and two anonymous reviewers for their helpful comments on an earlier draft of this manuscript.

Literature Cited

Bansal, A., P. Illukpitiya, S. Singh, and F. Tegegne. 2013. Economic competitiveness of ethanol production from cellulosic feedstock in Tennessee. Renewable Energy 59:53–57.

Bohanec, M., A. Messéan, S. Scatasta, F. Agevin, B. Griffits, P. H. Krogg, M. Žnidaršič, and S. Džeroski. 2008. A qualitative multi-attribute model for economic and ecological assessment of genetically modified crops. Ecological Modelling 215:247–261.

Bohanec, M., M. Žnidaršič, V. Rajkovič, I. Bratko, and B. Zupan. 2013. DEX methodology: three decades of qualitative multi-attribute modeling. Informatica 37:49–54.

Clark, C. D., B. C. English, and C. D. Garland. 2007. Competitive bidding as a means of extracting and demonstrating farmer willingness-to-grow an alternative crop. Journal of Extension 45:2IAWS.

Clayton, M. J. 1997. Delphi: a technique to harness expert opinion for critical decision-making tasks in education. Educational Psychology 17:373–386.

Dale, B. E., and R. G. Ong. 2012. Energy, wealth, and human development: why and how biomass pretreatment research must improve. Biotechnology Progress 28:893–898.

Dale, V. H., K. L. Kline, L. L. Wright, R. D. Perlack, M. Downing, and R. L. Graham. 2011. Interactions among bioenergy feedstock choices, landscape dynamics, and land use. Ecological Applications 21:1039–1054.

Dale, V. H., R. A. Efroymson, K. L. Kline, M. H. Langholtz, P. N. Leiby, G. A. Oladosu, M. R. Davis, M. E. Downing, and M. R. Hilliard. 2013. Indicators for assessing socioeconomic sustainability of bioenergy systems: a short list of practical measures. Ecological Indicators 26:87–102.

Efroymson, R. A., V. H. Dale, K. L. Kline, A. C. McBride, J. M. Bielicki, R. L. Smith, E. S. Parish, P. E. Schweizer, and D. E. Shaw. 2013. Environmental indicators of sustainability: what about context? Environmental Management 51:291–306.

English, B. C., T.-H. E. Yu, J. A. Larson, R. J. Menard, and Y. Gao. 2013. Economic impacts of using switchgrass as a feedstock for ethanol production: a case study located in East Tennessee. Economics Research International 2013:14; http://dx.doi.org/10.1155/2013/138485.

Florin, M. J., G. W. J. van de Ven, and M. K. van Ittersum. 2014. What drives sustainable biofuels? A review of indicator assessments of biofuel production systems involving smallholder farms. Environmental Science & Policy 37:142–157.

Groot, J. C. J., and W. A. H. Rossing. 2011. Model-aided learning for adaptive management of natural resources: an evolutionary design perspective. Methods in Ecology and Evolution 2:643–650.

Lewis, K. C., and R. D. Porter. 2014. Global approaches to addressing biofuel-related invasive species risks and incorporation into US laws and policies. Ecological Monographs 84:171–201.

MacMillan, D. C., and K. Marshall. 2006. The Delphi process–an expert-based approach to ecological modelling in data-poor environments. Animal Conservation 9:11–19.

Martinez, D. M., and B. W. Ebenhack. 2008. Understanding the role of energy consumption in human development through the use of saturation phenomena. Energy Policy 36:1430–1435.

McBride, A. C., et al. 2011. Indicators to support environmental sustainability of bioenergy systems. Ecological Indicators 11:1277–1289.

McLaughlin, S. B., and M. E. Walsh. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy 14:317–324.

Pelzer, E., et al. 2012. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. Ecological Indicators 18:171–182.

Qualls, D., K. Jensen, C. Clark, B. English, J. Larson, and S. Yen. 2012. Analysis of factors affecting willingness to produce switchgrass in the southeastern United States. Biomass and Bioenergy 39:159–167.

Reed, D. 2012. Life-cycle assessment in government policy in the United States. Doctoral Dissertation. University of Tennessee, Knoxville, Tennessee, USA. http://trace.tennessee.edu/utk_graddiss/1394/.

Robertson, G. P., and S. M. Swinton. 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Frontiers in Ecology and the Environment 3:38–46.

Tiller, K. 2011. Tennessee case study in full-scale development and integration of switchgrass feedstocks with biorefinery operations: genera energy and UT biofuels initiative. Industrial Biotechnology 7:357–364.

Tolbert, V. R., D. E. Todd Jr, L. K. Mann, C. M. Jawdy, D. A. Mays, R. Malik, W. Bandaranayake, A. Houston, D. Tyler, and D. E. Pettry. 2002. Changes in soil quality and below-ground carbon storage with conversion of traditional agricultural crop lands to bioenergy crop production. Environmental Pollution 116:S97–S106.

UT Agricultural Extension Service. 2001. PB443 corn production in Tennessee. PB443-3M-6/01(Rev) E12-525-00-032-01. The University of Tennessee, Knoxville, Tennessee, USA. http://trace.tennessee.edu/utk_agexcrop/42.

Vasileiadis, V. P., et al. 2013. Sustainability of European maize-based cropping systems: economic, environmental and social assessment of current and proposed innovative IPM-based systems. European Journal of Agronomy 48:1–11.

Velandia, M., D. M. Lambert, J. Fox, J. C. Walton, and E. K. Sanford. 2010. Intent to continue growing switchgrass as a dedicated energy crop: a survey of switchgrass producers in East Tennessee. European Journal of Social Sciences 15:299–312.

Wang, M., J. Han, J. B. Dunn, H. Cai, and A. Elgowainy. 2012. Wells-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environmental Research Letters Environ. Res. Lett. 7 (2012) 045905 (13pp); http://dx.doi.org/10.1088/1748-9326/7/4/045905.

West, A. S. 2011. Avian response to production stands of native warm-season grasses in the Mid-South. Master's Thesis. University of Tennessee, Knoxville, Tennessee, USA. http://trace.tennessee.edu/utk_gradthes/1036/.

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