Running Head: Multimetric aspects of sustainability

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

Authors:

Esther S. Parish, Center for BioEnergy Sustainability, Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831 USA[1]

Virginia H. Dale, Center for BioEnergy Sustainability, Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831 USA[2]

Burton C. English, Agricultural and Resource Economics Department, The University of Tennessee Institute of Agriculture, 2621 Morgan Circle, Knoxville, Tennessee 37996 USA[3]

Samuel W. Jackson, Genera Energy Inc., 167 Tellico Port Road, Vonore, Tennessee 37885 USA[4]

Donald D. Tyler, West Tennessee Research and Agricultural Station, 605 Airways Boulevard, Jackson, Tennessee 38301 USA[5]

---

[1] E-mail: parishes@ornl.gov

[2] E-mail: dalevh@ornl.gov

[3] E-mail: benglish@utk.edu

[4] E-mail: sjackson@generaenergy.com

[5] E-mail: dtyler@utk.edu

ABSTRACT

This paper connects the science of sustainability theory with applied aspects of sustainability deployment. A suite of 35 sustainability indicators spanning six environmental, three economic, and three social categories has been proposed for comparing the sustainability of bioenergy production systems across different feedstock types and locations. A recent demonstration-scale switchgrass-to-ethanol production system located in East Tennessee is used to assess the availability of sustainability indicator data and associated measurements for the feedstock production and logistics portions of the biofuel supply chain. Knowledge pertaining to the available indicators is 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 are determined for the overall trajectory of this bioenergy system's sustainability under each scenario. Within this East Tennessee context, switchgrass production shows potential for improving environmental and social sustainability trajectories without adverse economic impacts, thereby leading to potential for overall enhancement in sustainability within this local agricultural system. Given the early stages of cellulosic ethanol production, it is currently difficult to determine quantitative values for all 35 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.

Keywords: sustainability, multimetric, scale, indicators, bioenergy crop, biofuels, decision support, switchgrass, cellulosic ethanol

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 (Dale et al. 2012, Martinex and Ebenhack 2008). 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 paper connects the science of sustainability theory with applied aspects of sustainable deployment of bioenergy production systems.

The United States (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 transportation 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. Context-specific indicator information within a hierarchical decision tree framework is aggregated 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 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.

CASE STUDY DESCRIPTION

This sustainability evaluation focuses on a demonstration-scale switchgrass-to-ethanol experiment located within an eleven-county area of East Tennessee found in the Southeastern U.S. (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 grown switchgrass under contract (Clark et al. 2007). The Vonore, Tennessee, biorefinery, currently operated by DuPont Cellulosic Ethanol, opened in 2010 and has 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 Vonore biorefinery was constructed within the pre-existing Monroe County Niles Ferry Industrial Park with ready access to barge traffic, highways and a railway system. The cellulosic transportation fuel produced by this Vonore biorefinery is utilized as E-85 fuel in the University of Tennessee Motor Pool fleet. 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 biomass types, including switchgrass (Tiller 2011).

Simultaneous with the Vonore biorefinery construction beginning in 2007, three rounds of three-year contracts to grow switchgrass were offered to East Tennessee farmers within an approximately one-hour's drive of the facility (Fig. 2). The 'fuelshed' for this project, i.e., the total land area considered for providing dedicated biomass, therefore 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 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.

University of Tennessee Institute of Agriculture (UTIA) Extension Agents worked closely with the selected farmers to teach them how to manage this "new" crop of warm-season perennial grass, which is native to the area. 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 to 18 MT/ha (6 to 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 (personal communication by C. Clark on 1 July 2014).

Switchgrass was selected as the dedicated bioenergy crop for this East Tennessee experiment for a variety of reasons. More than 30 years' worth of lab- and field-based studies of switchgrass have shown that this perennial crop 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 its long root systems, and the potential to improve water quality (McLaughlin et al. 1998, Tolbert et al. 2002, Dale et al. 2011). Switchgrass has a lifespan of up to 20 years 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 (see ongoing study descriptions by The University of Tennessee's Center for Native Grasslands Management at http://nativegrasses.utk.edu). The lowland variety of switchgrass, Alamo, was selected for this experiment due to its higher yields and suitability for southern climate.

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).

For this sustainability assessment of the five-year Vonore switchgrass-to-ethanol experiment, we limited our analysis to the feedstock production and logistics portions of the supply chain (i.e., field to biorefinery gate; Fig. 1) where a variety of data were most available. We evaluated the bioenergy production system's sustainability relative to two alternative business-as-usual five-year agricultural production scenarios: 2023 ha (5000 acres) of traditional row crop production (i.e., tilled corn production) and 2023 ha (5000 acres) of unmanaged pasture. The key similarities and differences between these 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 U.S. (e.g., the Midwest), as demonstrated by the fact that average annual corn grain yields for this region were up to 50% lower than the U.S. national average over the past 15 years (Table 2).

EVALUATION FRAMEWORK

We built a qualitative sustainability evaluation framework known as a multi-attribute decision support system (MADSS) for our case study using DEXi 4.0 software (this tool is freely available from http://www-ai.ijs.si/MarkoBohanec/dexi.html). 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 multi-criteria 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). 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).

DEXi allows the evaluation of multiple options by decomposing the decision problem into more easily solved sub-problems. This decomposition is done by creating a hierarchical decision tree with attributes and ratings (called “scales” by the software) attached to each branch. We placed the overall “sustainability” rating (with possible values of “high sustainability,” “intermediate sustainability,” and “low sustainability”) that influences decisions regarding management changes at the top of the decision tree supported by three main branches for the three pillars of environmental, economic and social sustainability and multiple sub-branches extending below each of these three sustainability “pillars” (Fig. 3). We incorporated context-specific information pertaining to six categories of environmental indicators (McBride et al. 2011), three categories of economic indicators (Dale et al. 2013), and three categories of social indicators (Dale et al. 2013) within a hierarchical aggregation framework so that we could use our MADSS to explore the sustainability trajectory of the case study bioenergy production system relative to 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 data collection and analysis, 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 above-ground 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), sediment, herbicide], “Water Availability” (including base flow and consumption), and “Peak Storm Flow.” We combined measurements of suspended particulate matter less than 2.5 microns and 10 microns 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.” 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, we used a modified Delphi process to achieve a consensus of opinion amongst participants within their range of expertise (Clayton 1997, MacMillan and Marshall 2006). 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 discussing the indicators with each co-author one-on-one according to his/her expertise, and then organizing three round-table discussions over a five-week period during which time the co-authors collectively discussed and modified the sustainability indicator values, scenario parameters and 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.

EVALUATION OF ENVIRONMENTAL INDICATORS

Environmental sustainability indicator data were gathered for the case study according to the list of 19 indicators in six categories recommended by McBride et al. (2011). The environmental indicator values presented in Table 3 are meant to represent conditions over the five-year period of the Vonore switchgrass-to-ethanol experiment (i.e., 2008 to 2013) and are based on a combination of empirical data, modeling results, and scientific literature synthesized through expert opinion. The qualitative ratings for each environmental sustainability indicator have been formulated through a modified Delphi approach (Clayton 1997) and are intended to highlight the differences between the three alternative scenarios (Table 1), with special consideration given to observed or expected trends in indicator values measured over several years.

Soil Quality

Of the four recommended soil quality indicators, soil total organic carbon (TOC) is the most important to long-term soil sustainability in all systems (McBride et al. 2011). All four of the soil indicators are depth-dependent and vary according to underlying soil type, previous land use and management regimes, weather conditions, and other factors. Two datasets were used to assess TOC changes beneath the Vonore-area switchgrass fields, including a dataset from seven farms of the original 16 farms planted in 2008 and a dataset from 11 farms planted in 2010. Literature was then used to evaluate these TOC values relative to expected TOC values for tilled corn and unmanaged pasture.

Prior to the establishment of switchgrass on 292 ha (725 acres) of farmland selected for the first round of Vonore-area switchgrass plantings in spring 2008, D. Toliver et al. (unpublished manuscript) took randomized georeferenced plot measurements of TOC at a series of shallow depths (0-30 cm) and deep depths (30-120 cm). These TOC measurements were then repeated after harvest each year for four years following switchgrass establishment. The seven sampled switchgrass farms differed with respect to size, soil type, previous land use, and till/no-till management. TOC averaged across the 0-120 cm soil profile for all sample locations showed a slight increase from about 70 Mg/ha to 77 Mg/ha after three years, but the change was not statistically significant at $\rho \geq 0.10$. Data from the farms planted in 2008 show that soil carbon accumulates at different rates across the soil depth profile (Soro 2011).

Measurements of percent organic matter (%OM) were taken at depths of 15-20 cm (6-8 in.) by a separate group of UTIA researchers from a set of 11 switchgrass farms planted in Spring 2010 (unpublished data). Although no measurements were taken prior to land conversion, 120 sampling locations across the 274 ha (676 acres) were examined once per year for three consecutive winters following switchgrass planting. The %OM measurements were divided by 1.72 in order to convert them to percent total organic carbon (TOC) measurements, and an average bulk density measurement of 1.20 g/cm^3 [acquired by averaging the 220 bulk density measurements taken at a depth of 15-30 cm (6-12 in.) prior to the 2008 plantings] was used to calculate TOC in the desired units of Mg/ha. Using a paired sample T test, we tested the hypothesis that no change in soil carbon levels occurred over the three-year sampling period. Although there was no significant change in TOC from December 2011 to January 2013, the average 10.5 Mg/ha increase in TOC observed between December 2010 and January 2013 was significant at a shallow depth ($\rho < 0.05$, $n = 120$).

Previous experiments have demonstrated that perennial switchgrass can improve soil conditions and increase soil OM content relative to tilled corn (Tolbert et al. 2002). A study comparing carbon sequestration by four-year-old switchgrass adjacent to annually harvested corn at two different sites in southern Quebec showed that switchgrass of the Cave-in-the-Rock variety sequestered carbon at a rate of 3 tons/ha/year more than the corn and 3.5 tons/ha/year more than nearby fallow land, irrespective of the differences in soil type and environmental conditions found at the two locations (Zan et al. 2001). While both corn and switchgrass had high above-ground carbon storage, switchgrass demonstrated higher below-ground and overall carbon storage than corn (Zan et al. 2001). We would, therefore, expect the Vonore-area no-till switchgrass farm soil profiles to show increases in TOC relative to tilled corn and unmanaged pasture over a period of several years due to the slow incorporation of above-ground litter and deep roots.

We removed the soil total nitrogen (N) indicator from the sustainability decision tree due to a lack of measurements from the Vonore switchgrass farms. However, total N is likely to be positively correlated with TOC because organic compounds contain nitrogen in addition to carbon (Mullen et al. 1998). Total N changes very slowly (over many years) and is generally about 0.14% to 0.21% of the total soil mass (personal observations by D. Tyler).

Phosphorus content of soils underlying the 2008 and 2010 sets of switchgrass farms was measured in pounds per acre using the Mehlich 1 soil test method (Wolf and Baker 1985). Average values ranged from 0 to 0.06 Mg/ha at depth of 15-20 (6-8 in.) over the 3 years measured at the 2010 farms (n=120). However, extractable P measurements may not be that useful for comparing different bioenergy production systems because biases in the soil sampling methods and P extraction methodology tend to vary by state, farmer, and laboratory (personal observations by D. Tyler). The low, medium and high (L, M, H) phosphorus ratings provided to farmers may actually be more useful for assessing the sustainability of extractable P levels and associated management choices.

The UTIA "Guidebook for Sustainable Production Practices of Switchgrass in the Southeastern U.S." [available from the Southeastern Partnership for Integrated Biomass Supply Systems (IBSS) at http://www.se-ibss.org/] and the UT Agricultural Extension Service recommend that no phosphate (P) or potassium (K) be added to switchgrass fields until the soil test comes back "Low" for P and K; at that point, only enough fertilizer to produce a yield of 18 MT/ha (8 tons/acre) of switchgrass [i.e., 44 kg/ha (40 pounds/acre) of P and/or 88 kg/ha (80 pounds/acre) of K] should be added to the soil (see Factsheet SP701-A, "Growing and Harvesting Switchgrass for Ethanol Production in Tennessee" available from https://extension.tennessee.edu/publications/). The overall management goal is to add fertilizer to the switchgrass equivalent to removal rates. By contrast, current UT Agricultural Extension Service guidelines for corn (UT PB443, "Corn Production in Tennessee") suggest adding 110-176 kg/ha (100-160 pounds/acre) of P when the soil test comes back "Low." Soil P is heavily manipulated by humans and does not greatly impact the health of the soil itself. Sustainability is more likely to be affected by the potential for excess P to be transported into nearby waterways.

This potential impact is more likely to occur under tilled corn production (since more P is added to the system overall), and least likely to occur for unmanaged pasture (since no P is added to the system).

Although bulk density (BD) measurements were taken from seven Vonore-area farms prior to the 2008 switchgrass plantings, no changes in BD were assessed during the experiment. BD can decrease soil's available water content if it becomes too low and can restrict root growth if it becomes too high, making either extreme unsustainable. But no evidence of either of these extremes has been seen in this area of East Tennessee, except in a few instances when fields were bordered by heavily traveled roads (personal observations by D. Tyler). Typical BD measurements for Tennessee range 1.35 to 1.5 g/cm^3, and BD measured prior to the 2008 Vonore-area plantings averaged 1.2 g/cm^3. Therefore, we determined this BD indicator to be "nonrestrictive" with an intermediate sustainability rating for all three of the agricultural scenarios (Table 3).

Water Quality and Quantity

Seven recommended sustainability indicators related to water quality and quantity were evaluated based on a combination of empirical data and modeling analysis with the Soil & Water Assessment Tool (SWAT). Water quality and flow data were collected from the 247.5-hectare Lenoir City catchment from July 2012 to March 2014 as part of the USDA-funded Southeastern Partnership for Integrated Biomass Supply Systems (IBSS) project. These data showed average in-stream concentrations of 0.15 mg/L for total P, 1.62 mg/L for total N, and 62 mg/L for sediment. The Lenoir City catchment lies within the larger (272,600 ha) Lower Little Tennessee watershed that was the focal area for the development of a landscape design tool called the Biomass Location for Optimal Sustainability Model (BLOSM) previously used to evaluate the possibility of strategically placing switchgrass plantings across the watershed to minimize total N, total P, and total sediment concentrations simultaneously with maximizing overall economic profit for the watershed (Parish et al. 2012). In the absence of definitive Tennessee guidance for maximum stream nutrient concentrations, water-quality threshold values used for BLOSM were based on potential thresholds of stream eutrophication described by Dodds (2009): 1.0 mg/L for TN, 0.1 mg/L for TP, and 50 mg/Lfor TSS. Thus, the nutrient and sediment concentrations at the outlet of the Lenoir City catchment are higher than the BLOSM targets (Parish et al. 2012); however, no water quality data were taken prior to the 2010 switchgrass plantings to use for comparison.

SWAT was used to evaluate potential water quality differences resulting from no-till switchgrass, no-till corn and managed pasture/hay planted on the 5% of the Lenoir City catchment that was converted to switchgrass in 2010. Note that the management parameters used in these SWAT runs differ slightly from the alternative scenarios presented in Table 1 and are therefore a representative example. First, SWAT was calibrated using the IBSS stream flow data acquired from the catchment. Then SWAT was used to model in-stream concentrations of nitrate, phosphorus, and sediment over a period of five years (January 2010 to December 2014). A comparison of results from the three SWAT runs showed lower in-stream concentrations of sediment, nitrate and total phosphorus (P) when the land was under no-till switchgrass rather than no-till corn (lower by 15%, 20%, and 21%, respectively), and we would expect the sediment and nutrient reductions to be even greater for no-till switchgrass relative to tilled corn. Water quality modeling results for managed hay/pasture and switchgrass were nearly identical with the exception of nitrate concentrations, which were 8% lower for switchgrass. Although nitrate concentrations were not measured by IBSS, they can be approximated using the SWAT run based on actual switchgrass locations. After five years of switchgrass production, the nitrate concentration at the outlet of the catchment was calculated to be 0.15 mg/L.

Nutrient export data were collected from three sample sites downslope of switchgrass fields around Vonore from April 2013 to March 2014 as part the IBSS project. Located in Monroe County, Tennessee, the Thompson farm is primarily underlain by Decatur Silty Clay Loams and Decatur Silt Loams and receives about 129 cm (50.8 in) of rainfall each year. Based on 12 runoff events collected over the one-year period, Hayes (2014) found that the average TN of runoff captured from the field was 5.9 mg/L (with a range from 0.159 mg/L to 18.635 mg/L) and the average total P (TP) of runoff collected from the field was 2.3 mg/L (with a range from 0.108 mg/L to 8.930 mg/L). Hayes calculated an expected load of TP ranging from 0.11 g/Ha to 400 g/Ha (average mean = 0.13 kg/Ha) and an expected load of TN ranging from 0.0007 g/Ha to 1519 g/Ha (average mean = 0.36 kg/Ha) and concluded that all of these values are lower than those recorded for traditional row crops. Hayes calculated a cover-management (C) factor of 0.0006 for the Thompson switchgrass field and interpreted this value to mean that switchgrass is likely to reduce the field's erosion by over 99%, thereby causing a reduction in stream sediment concentrations. Overall, these data indicate that the East Tennessee switchgrass farms are reducing erosion and nutrient runoff, thereby improving hydrological conditions.

Weed control through herbicide application is essential during switchgrass establishment but is rarely needed after the first year of production (see Factsheet SP701-A, "Growing and Harvesting Switchgrass for Ethanol Production in Tennessee" available from https://extension.tennessee.edu/publications/). Herbicide applications for switchgrass are therefore similar to corn for the first year but zero out for the remaining ten years or more of production. No herbicide export or in-stream concentration measurements were taken as part of the Vonore experiment, but we would expect herbicide concentrations from switchgrass fields to decrease over time relative to corn fields and to be somewhat higher than unmanaged pasture (which uses no herbicide at all).

While conducting a cradle-to-grave life-cycle inventory (LCI) of switchgrass fuel pellet production in the Southeastern U.S. as part of his dissertation, Reed (2012) collected survey data from 12 Vonore-area farmers with 152 ha (376 acres) of three-year average switchgrass production at a three-year average yield of 14 MT/ha (6.2 tons/acre). He found that the farmers applied an average of 0.045 kg (0.10 pounds) of glyphosate herbicide per ton of switchgrass produced. Assuming 2023 ha (5000 acres) of switchgrass production at a yield of 14 MT/ha (6.2 tons/acre), this would mean a total application of 1406 kg (3100 pounds) of glyphosate spread over an eleven-county area and staggered over the three-year switchgrass establishment period, i.e., a one-time application of 0.7 kg/ha for the entire experiment.

Glyphosate has been a popular herbicide for over 60 years because it is taken up quickly by growing plants and does not cause lead to any known toxic, carcinogenic or reproductive health problems in human populations (Duke and Powles 2008). Therefore, we would not expect herbicide use to have much impact on the overall sustainability of this switchgrass-to-ethanol experiment.

Peak storm flow can be indicative of increased runoff, land surface erosion, and/or stream channel scouring associated with land-use change. Peak flow and base flow indicators (Table 3) were based on composite discharge data collected intermittently from Notchy Creek over a two-year period. Notchy Creek drains an area containing nearly 70% switchgrass cover planted in 2008. The highest maximum value was used to represent the peak storm flow indicator (i.e., 6769 L/s) and the lowest minimum value was used to represent the indicator of minimum base flow (i.e., 203 L/s). The graph of daily average values shows that the Notchy discharge averaged between 210 L/s and 1009 L/s over the period of record.

The experimental work by Hayes (2014) indicates that switchgrass land cover in East Tennessee has extremely low erosive potential. A lack of flow data prior to the switchgrass plantings makes it difficult to assess changes in runoff patterns for this catchment, however, so we turn to literature for a relative comparison. Past measurements in Iowa have shown that soil losses from corn can exceed losses from grasslands by over 70 times under normal hydrologic conditions and by over 200 times during heavy rains (McLaughlin and Welsch 1998). The recognition that switchgrass can reduce overland flow of runoff from agricultural fields has led to its use as protective buffer around wetlands in the Northern Great Plains (McLaughlin and Welsch 1998). Therefore, we rated no-till switchgrass as having an improved capacity to absorb excess water relative to tilled corn and unmanaged pasture (Table 4).

Analysis of water requirements along each step of the bioenergy supply chain indicates that the water transpired by bioenergy crop during its growth may be the largest portion of the water consumed, amounting to as much as 99% of the overall water requirements for corn ethanol production (King et al. 2013, Mubako and Lant 2008). Switchgrass is a native, drought-tolerant species that has proven capable of growing during hot summer months when other crops may be limited by water availability (McLaughlin and Walsh 1998), and the Alamo variety of switchgrass has been found to use water particularly efficiently (McLaughlin and Kszos 2005). Certainly, the Vonore-area Alamo switchgrass plantings thrived despite their establishment during a period of unusually prolonged drought. However, no field measurements of water consumption (e.g., evapotranspiration rates) were collected during from this area, so we turn to modeling work and literature to estimate the water use of switchgrass relative to corn and hay.

The SWAT model runs of the three alternative scenarios for the Lenoir City catchment described earlier as well as the modeling work conducted for the larger Lower Little Tennessee Watershed (Parish et al. 2012) found negligible impact on average stream flow from no-till switchgrass production relative to no-till corn and hay production. Our literature review turned up very few studies of water use efficiency of different cellulosic bioenergy crops within different contexts. During their review of published data for the development of an integrated spreadsheet-based model to estimate the total water requirement for 12 biomass conversion pathways, Singh and Kumar (2011) found nine field-based studies from the U.S. and Canada that estimated the total crop water requirement for corn production to range between 481 and 943 mm. However, the authors did not record any similar studies of switchgrass water requirements. Modeling work by Kiniry et al. (2008) to compare the water use efficiency of corn and switchgrass production at five U.S. locations determined that switchgrass has a much greater water use efficiency than corn grain, with values ranging from 3-5 mg/g for four different varieties of switchgrass. A review of peer-reviewed literature by King et al. (2013) reported that switchgrass’s ratio of mean annual precipitation to actual evapotranspiration is 1.0, its mean stand water-use efficiency is 22.8 kg/mm, and its overall water-use efficiency at the farm gate is 42.2 MJ/m^3, although the authors noted that data pertaining to the ecophysiology and ecosystem-scale water cycling of C4 grasses are extremely limited. Based on these literature values, we rated switchgrass as having “highly efficient water use” compared to tilled corn and unmanaged pasture (using alfalfa, a C3 species, as a representative example). However, current water consumption by corn and hay within this East Tennessee context of generally abundant rainfall and surface water is not a problem at present, although it is currently unclear if East Tennessee will become drier or wetter under projected climate change scenarios (Behrman et al. 2013). It is possible that within this East Tennessee context water consumption could be more of a sustainability consideration for biorefinery operations (which were not considered in this analysis) than it is for crop production and logistics.

Air Quality

For this case study, primary air quality concerns are related to vehicle emissions from heavy equipment in the field and to the potentially large number of trips by trucks required to transport the low-density switchgrass material to the biorefinery. Using surveys collected from 12 of the Vonore-area switchgrass farms, Reed (2012) conducted a cradle-to-gate life cycle inventory (LCI) of air emissions for switchgrass stand establishment, crop transportation, drying, and pelletization. Reed reported PM emissions for switchgrass growth and harvest as 0.004 kg $PM_{2.5}$ per ton of switchgrass produced. Given an average yield of 14 MT/ha (6.2 tons/acre) across 2023 ha (5000 acres), which would amount to a total annual generation of 124 kg (0.12 MT) of $PM_{2.5}$ for growth and harvesting operations.

Using a least-cost logistics model in conjunction with the EPA MOVES model, Yu et al. (unpublished manuscript) modeled potential changes to air quality resulting from truck traffic associated with a commercial-scale (50 Mgal/year) biorefinery sited in Vonore. They found that emissions of $PM_{2.5}$ increased an average of 6.58 MT/year and PM_{10} increased an average of 7.34 MT/year throughout the surrounding 13 counties due to an additional 100,000 truck trips per year. Since the Vonore biorefinery has a capacity of nearly 1 million L (250,000 gal) per year, we estimate that only 0.5% (250,000/50M) of these air emissions increases would occur for this case study. Thus, 0.033 MT/year of $PM_{2.5}$ and 0.037 MT/year of PM_{10} would be attributable to transportation logistics. Genera Energy has measured $PM_{2.5}$ and PM_{10} emissions from its handling facility as 0.052 MT/year and 0 MT/year respectively following the removal of 99.9%

of all particulate matter via its dust control system. Totaling these PM quantities across the feedstock production, transportation and logistics portions of the supply chain (Figure 1) therefore amounts to $PM_{2.5}$ emissions of 0.209 MT/year and PM_{10} emissions of 0.037 MT/year for the no-till switchgrass scenario.

No quantitative estimates of PM emissions from Vonore-area corn producers were available for direct comparison. Since the majority of the switchgrass scenario's PM emissions are attributable to the in-field harvesting equipment, however, we rated unmanaged pasture as having low PM emissions (since the crop is harvested by cattle) and tilled corn as having higher PM emissions than switchgrass (since it has to be both planted and harvested each year) (Table 5).

Productivity

An ecological measurement of above-ground net primary productivity (ANPP) can be calculated from crop yields based on the typical carbon content of the plant. Around Vonore, full yields of switchgrass were attained by the third year and averaged 13-18 MT/ha (6-8 tons/acre), i.e., enough biomass to produce ethanol at approximately 4678 L/ha (500 gal/acre). With a typical lignin content of 22%, we calculate that mature East Tennessee switchgrass has a typical ANPP of approximately 394.5 g C/m^2/year.

Biodiversity

Biodiversity can refer to the variety and abundance of organisms found in an agroecosystem, whether they are plants, animals, fungi or even microbes (McBride et al. 2011). In this case study context, increased biodiversity means an increased variety and abundance of birds, small mammals and pollinators and does not involve any species of regulatory concern. Switchgrass harvesting occurs in November (or after the first killing frost) and therefore does not disturb the nesting of certain avian species. Switchgrass' growth structure provides a combination of undisturbed vertical nesting for birds and sheltered open spaces for young birds and small mammals (Rupp et al. 2012). Switchgrass fields are somewhat more attractive to a variety of species than unmanaged pasture (which tends to have patchy cover) , and much more attractive to a variety of species than tilled corn fields, which are often reported to have low avian richness, very low abundances of breeding birds, and a paucity of nesting birds (Rupp et al. 2012). Vonore-area switchgrass producers noticed the return of quail to fields where they had not been seen for years (Tiller 2011).

UT student Andrew West (2011) studied avian responses using data collected from several of the East Tennessee switchgrass fields during 2009 and 2010. Through comparison of bird metrics (relative abundance, species diversity, and species richness) and vegetation metrics (average height, litter depth, vertical cover, litter cover, and vegetation cover) across five treatments (including switchgrass), West determined that management practices such as vegetation height and litter depth influence some species and not others. Field sparrows (*Spizella pusilla*) were less abundant in biofuel production areas than in the control, hay and graze treatments, whereas eastern meadowlarks (*Sturnella magna*) and dickcissels (*Spiza americana*) were more abundant in seed fields.

A series of first and second bioenergy cropping scenarios modeled in the 16,000 km^2 Sagninaw River watershed of lower Michigan showed that production of switchgrass on marginal lands and on a combination of marginal and agricultural lands increased EPT richness (i.e., the number of distinct taxa in the insect orders Ephemeroptera, Plecoptera, and Trichoptera) as compared to corn/soybean rotations (Einheuser et al. 2013). An ongoing Oak Ridge National Laboratory analysis of macroinvertebrate data gathered across Tennessee has shown correlation between measurements of EPT richness and several water quality criteria (i.e., total nitrogen, total phosphorus, ammonia, nitrogen dioxide and sediment) within the Ridge and Valley ecoregion that crosses this East Tennessee area (personal communication with L. Baskaran). Thus, we considered it likely that the lower nutrient requirements and lower erosion rates demonstrated by the switchgrass fields will ultimately translate into higher EPT richness.

Greenhouse Gases

Reed (2012) prepared a life cycle inventory of air emissions for switchgrass stand establishment and transportation to a handling facility based on a survey of 12 Vonore-area farmers. He assumed a ten-year growth period (with growth plateauing after year three), an average yield of 14 MT/ha (6.2 tons/acre), and an average transportation distance of 80 km (50 miles). Reed's unit of analysis was one ton of switchgrass pellets, but he stated that each ton of pellets was derived from one ton of (dry) switchgrass that had been transported to the pelletization facility. Reed reported CO_2 emissions in kg per ton of switchgrass and divided his results for switchgrass growth and harvest into fossil-based (5.39 kg) and biomass-based (0.073 kg) CO_2 emissions. Reed also reported emissions of methane, another potent greenhouse gas, as being 0.106 kg per tons of switchgrass (pellets) produced.

Although not required to do so by permit, Genera Energy has calculated its emissions impact from electricity for preprocessing switchgrass as 67.6 MT of CO_2-equivalent and its emissions impact from diesel consumption as an additional 36.2 MT of CO_2 equivalent. The total projected emissions from biomass handling on an annual basis for this case study would therefore be 103.8 MT of CO_2-equivalent.

A national-scale life cycle assessment of greenhouse gas (GHG) emissions from five bioenergy feedstocks used to make ethanol indicated that non-irrigated switchgrass produced over a 30-year period can reduce life-cycle GHG emissions by 77-97% relative to petroleum gasoline (Wang et al. 2012). Wang et al. (2012) also reported that land-use change for switchgrass ethanol production results in 1.3 g CO_2 e per MJ of ethanol (grams CO_2 emitted per unit of energy), whereas land-use change for corn ethanol production results in 9.1 g CO2e per MJ of ethanol. Therefore, we ranked GHG emissions for our no-till switchgrass scenario as being intermediate relative to lower (no) GHG emissions for unmanaged pasture and higher GHG emissions for tilled corn production (Table 5).

EVALUATION OF SOCIOECONOMIC INDICATORS

Socioeconomic sustainability indicator data for the case study were gathered according to the list of 16 indicators in six categories recommended by Dale et al. (2013), with three social categories and three economic categories that can be difficult to disentangle. The social and economic indicator values presented in Table 4 are meant to represent conditions over the five-year period and are based on a combination of empirical data, modeling results, and literature review synthesized through expert opinion. Just like the environmental indicators, the qualitative ratings for each socioeconomic sustainability indicator have been formulated through a modified Delphi approach (Clayton 1997) and are intended to highlight the differences between the three alternative scenarios (Table 1), with special consideration given to observed or expected trends in indicator values measured over several years.

Social Well-being

We used the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service's (NRCS's) Impact Analysis for Planning (IMPLAN) model and the scenario assumptions listed in Table 1 to compare the impacts of growing 2023 ha (5000 acres) of no-till switchgrass, tilled corn, and unmanaged pasture on local income and jobs created. Conducting an analysis by parts, the direct economic impact of growing and harvesting 2023 ha (5000 acres) of no-till switchgrass was estimated at $2,719,000 with 67 jobs created and the total impact was $5,205,000 with 96 jobs created. Using the average price for corn and pasture (with forage valued at the average hay price), 2023 ha (5000 acres) of conventional tilled corn had similar economic impacts to switchgrass while 2023 ha (5000 acres) of pastureland, not including the cattle that it supported, had a direct roughage impact valued at $892,974 and a total economic impact of $1,564,400 with an estimated 20 jobs created. We were unable to translate the number of agricultural jobs created into a measure of full-time equivalent (FTE) jobs, the recommended measurement unit for the 'employment' indicator (Dale et al. 2013). However, we assigned ratings of "more jobs" and "more household income" to the no-till switchgrass scenario because switchgrass is planted and harvested at times of the year when no other local agricultural work is available and can therefore be used to supplement household income.

'Work days lost due to injury' is another recommended indicator of social well-being (Dale et al. 2013). Genera Energy, which oversees both the agricultural and preprocessing operations for the Vonore-area switchgrass production, did not have a recordable injury in over 1,460 days of operation (as of 4 November 2014). According to the U.S. Bureau of Labor Statistics (www.bls.gov/iif/oshsum.htm), the 2012 recordable injury rate was 5.3 injuries per 100 workers for crop production and 5.3 injuries per 100 workers for agricultural support industries (e.g., transportation, equipment maintenance). In 2012, an average (median) of 7 days of work per year was missed due to an agriculture-related injury; the fatality rate was 22.8 per 100,000 full-time equivalent agricultural workers. These U.S. national rates apply to all agricultural activities and could not be differentiated between the three alternative scenarios. Therefore, we assigned an intermediate rating of "average work days lost" to all three scenarios.

Social Acceptability

A bioenergy production system cannot be sustained if the local community does not accept it (Dale et al. 2013). The category of social acceptability indicators is, therefore, intended to capture important values that are not explicitly considered in environmental and economic analyses, including aesthetic values, recreational values, cultural values, and public perceptions (Dale et al. 2013). Recommended measurements of social acceptability (Table 4) are particularly relevant to the feedstock production portion of the supply chain (Fig. 1) and include percent favorable opinion, transparency in the form of percent of indicators for which timely and relevant data are reported, effective stakeholder participation in the form of documented responses to concerns and suggestions, and the annual probability of the risk of a catastrophic event. Information was available to assign qualitative sustainability ratings to each of these social acceptability indicators for the switchgrass scenario, and all of these factors were positive. However, it is important to consider that this case study involves a noninvasive native perennial grass without any significant concerns about food security or genetic modification.

A direct measurement of the social acceptability of a bioenergy project can be obtained through surveys of public opinion (Dale et al. 2013) as well as through a competitive contract bid process designed to reveal farmer willingness to grow a selected bioenergy crop (Clark et al. 2007, Epplin et al. 2007). For this case study, we based our assessment of public opinion of switchgrass production on the lessons learned from 2005 surveys and competitive bids conducted in West Tennessee (Jensen et al. 2007, Qualls et al. 2012), 2009 competitive bids conducted in in East Tennessee (Jensen et al. 2011), results of surveys mailed to Tennessee producers in 2005 and to Southeastern producers (12 states, including Tennessee) in 2009 (Qualls et al. 2012), the results of several stakeholder focus groups held after switchgrass production was underway (personal observations by S. Jackson), and a series of face-to-face interviews conducted with East Tennessee farmers to determine their willingness to continue growing switchgrass following the expiration of their contracts (Fox et al. 2010, Velandia et al. 2010).

During the DOE-funded 2005 West Tennessee experiment, a mail survey of 3500 Tennessee producers was also used to collect information on perceptions of, and willingness to grow, switchgrass. Results indicated that 30% of Tennessee farmers were interested in producing switchgrass (as reported by Qualls et al. 2012). In 2009, a mail survey of randomly selected agricultural producers who reported at least $10,000 in sales and who operated at least 25 acres was conducted across 12 southeastern U.S. states (including Tennessee) with the sample drawn across the states in proportion to the state's agricultural sales (Qualls et al. 2012). A 19% response rate yielded 760 complete surveys suitable for Tobit censored regression analysis (Qualls et al. 2012). The average respondent was 59 years old with a 156 ha farm; 27% of respondents derived at least half of their income from farming and 60% from produced hay (Qualls et al. 2012). Results showed that 67% of southeastern respondents and 55% of Tennessee respondents were willing to produce switchgrass (Qualls et al. 2012). Thus, Tennessee farmer willingness to grow switchgrass seems to have increased from 2005 to 2009 (i.e., from 30% to 55%).

Southeastern farmers with hay equipment—and especially with idled hay equipment—expressed higher interest in the prospect of growing switchgrass, but, contrary to expectations, neither the amount of idle land possessed by the farmer nor former contracting experience showed any significant correlation with farmer interest (Qualls et al. 2012). Farmers who did not perceive significant erosion problems on their land were about 8% less likely to be interested in growing switchgrass (Qualls et al. 2012). Educational attainment was not a significant factor in farmer interest, but the more strongly the farmer considered himself/herself to be a late adopter of new technologies and crops, the less willing he/she was to convert land to switchgrass (Qualls et al. 2012). Based on the 2009 survey results, which showed that Southeastern farmers were willing to convert an average of 56 ha (or 36% of their total acreage) to switchgrass, it could take as many as 567 individual farmer contracts to establish a commercial-scale biorefinery in the Southeastern U.S. (Qualls et al. 2012).

The 2009 mailed survey of southeastern U.S. producers indicated that farmers considering switchgrass production were concerned about potential conflicts with planting and harvest times for other crops, having sufficient capacity to introduce a new crop, and introducing a perennial crop such as switchgrass on leased land, but that they were also motivated by the possibility that switchgrass might lower input use as well as by the possibility of improving national energy security by growing an alternative fuel feedstock (Qualls et al. 2012). Drawing from lessons learned from the 2005 and 2009 switchgrass experiments, Dr. Chris Clark of UTIA summarized the primary Tennessee producer concerns as unfamiliarity with the switchgrass as a crop, opportunity costs involved with converting from an annual to perennial crop, an undeveloped market/industry, and a lengthy establishment period (i.e., three years to attain full yield (personal communication).

Three rounds of three-year contracts were offered to East Tennessee farmers in 2007-2009, simultaneous with construction of the Vonore demonstration-scale biorefinery. For all three rounds, the number of applications exceeded the number of awarded contracts. The first two rounds of contracts offered a guaranteed price of \$1112/ha (\$450 per acre) for all three years of production, but the third and final round of contracts (i.e., for the Spring 2010 plantings) incentivized payments after the establishment year so that the farmer received $618/ha ($250/acre) + $44/MT ($40/ton) in year 2 and $371/ha ($150/acre) + $55/MT ($50/ton) in year three (presentation by C. Clark of UTIA). Sixteen producers with a total acreage of 293 ha (723 acres) across 49 fields were selected for Spring 2008 planting, 35 producers (11 repeat) with 765 ha (1890 acres) across 150 fields were selected for Spring 2009 planting, and 39 producers (18 repeat) with 1006 ha (2487 acres) across 199 fields were selected for Spring 2010 plantings (data provided by C. Clark of UTIA on 1 July 2014). The high number of repeat farmers indicates both continued willingness to grow switchgrass and the ability to produce a good harvest. Face-to-face interviews with the initial set of Vonore-area switchgrass producers found that 87% of them intended to continuing growing switchgrass after the expiration of their initial three-year contracts (Fox 2010, Velandia et al. 2010).

Environmental and socioeconomic goals can be achieved more effectively with longer-lasting effects when stakeholders actively participate in the planning and implementation phases of bioenergy projects (Dale et al. 2013). Agricultural Extension agents worked with each of the Vonore-area switchgrass producers to ensure an understanding of the needed crop management. Each farmer was required to keep detailed records of management practices used during the experiment. Multiple public meetings and focus groups were conducted to address stakeholder concerns. Thus, this switchgrass-to-ethanol experiment achieved the highest possible stakeholder involvement, and we gave it a “high stakeholder involvement” rating relative to “average stakeholder involvement” in ongoing corn and pasture production (Table 6).

Risk of catastrophe is measured as the annual probability of a catastrophic event the last of the recommended indicators of social acceptability (Table 4). Dale et al. (2013) define a catastrophic event related to bioenergy production as an event that "occurs suddenly and results in 10 or more human deaths, more than 1000 ha of land or water intensely disturbed, or detectable species extinction or extirpation." No catastrophic events of this magnitude have occurred during the five-year implementation of the Vonore-area switchgrass experiment. However, smaller magnitude events with potential to disrupt the biofuel supply chain prior to fuel conversion have either already occurred or might be expected within the near term, as evidenced through the insurance premiums paid by the Vonore biomass handling facility. We addressed the likelihood of these smaller system shocks as a measure of risk for our case study.

In March 2012, more than 1400 bales of switchgrass were purposely set on fire by two Monroe County residents who claimed to have been "bored" (per local TV news reports available online at www.WBIR.com). Destined for processing at the Biomass Innovation Park in Vonore, the lost bales were estimated to be worth $35,000 and might have produced more than 159,000 (42,000 gallons) of ethanol, or 17% of the biorefinery's annual operating capacity. Recent fires at the Abengoa facility in Kansas, during which $2 million-worth of inventory burned, as well as at the DuPont cellulosic biorefinery in Iowa show that fire is a real risk to bioenergy logistics.

In addition to considering storage and transportation risks (such as fire) that may occur after harvesting, crop risk ratings are assessed by insurance companies based on a combination of yield risk factors related to weather, pests and disease that may occur prior to harvesting. Relative to the business-as-usual alternatives of hay/pasture or row crop production, pre-harvest risk is high for corn, medium for switchgrass and low for pasture/hay (personal observations by S. Jackson). Post-harvest risk is low to medium for grain material (which is not very combustible), but medium to high for switchgrass and hay due to possibility of combustion resulting from lightning strikes, arson, etc. Conversely, disease/pest risk is low for switchgrass and hay and intermediate for corn (due to the potential for rootworms during the establishment phase). While some disease might be avoided through seed treatment and certification programs, the current lack of a seed certification program is not an issue for biofuel producers that choose to deal only with reputable seed companies (personal observations by S. Jackson).

Resource Conservation

Resource conservation indicators include the depletion of non-renewable energy resources (i.e., the amount of petroleum extracted per year) and the fossil energy return on investment (EROI), or the ratio of the amount of fossil energy inputs to the amount of useful energy output (MJ). A national modeling assessment by Argonne National Laboratory (Wang et al. 2012) calculated that the energy balance for the field to wheels production of ethanol from non-irrigated switchgrass is 21.0 MJ/liter, resulting in an overall EROI of 5.44 relative to a corn ethanol EROI of 1.61 and corn stover ethanol EROI of 4.77. A modeling assessment of a commercial-scale cellulosic biomass supply chain across the Southern U.S. calculated that the net energy ratio (fossil energy inputs to biomass energy delivered) for switchgrass delivered to a conversion facility at a rate of 500,000 bone dry tons per year would be 0.11 (Daystar et al. 2014). Our local modeling analysis using IMPLAN indicated that over nearly eight million liters of gasoline would be replaced through local cellulosic ethanol production each year, thereby leading to a net savings of fossil fuel resources.

Energy Security

Energy security is an inherently national issue that is more easily addressed across the entire fuel supply chain than at the feedstock production and logistics steps (Fig. 1). In 2011, nearly half of the petroleum consumed by the U.S. was imported from foreign countries and public opinion polls suggested that Americans regarded this dependence on foreign oil as a threat to national security (Jensen et al. 2012). Results of a 2009 national online survey with 914 usable responses representative of the general U.S. population distribution indicated that respondents strongly agreed (i.e., mean answer of 4.13 on a scale of 1 to 5) that reducing foreign oil is important to national security and that they were willing to pay about $0.032/mile less for E85 for each percentage point of the fuel that came from imports (Jensen et al. 2012). Rural respondents were more willing to pay for import reductions than urban dwellers, and consumers in the Midsouth (which includes Tennessee) were generally more willing to pay for import reductions than those respondents from the eastern seaboard area (Jensen et al. 2012). Willingness to reduce fuel imports through purchases of ethanol was less clear however, possibly due to a general lack of awareness that ethanol is manufactured domestically (Jensen et al. 2012).

In 2012, Tennesseans consumed about 1976 L/yr/person (522 gal/yr/person) of gasoline, making transportation fuel the second largest energy-consuming sector for the state, i.e., 28% of the State's total annual energy consumption of 284.3 MBTU (Bansal et al. 2013). This high dependency on gasoline makes Tennessee's citizens vulnerable to price fluctuations and shortages associated with petroleum production; thus, Tennessee's energy security might be improved through transportation fuel diversification with renewable energy options (e.g., ethanol production). If the annual harvest from 2023 ha (5000 acres) of switchgrass were converted to ethanol at a rate of 318 to 355 L/MT (76 to 85 gallons/short ton) and used within the region, over 7.6 million L (2 million gallons) of gasoline based on British thermal unit (BTU) content would be replaced by fuel produced within the region. Assuming a bulk price of $2.80/gallon for gasoline, over $5.1 - $5.8 million per year would not leave the region for the purchase of fuel. Thus, energy security would improve under the switchgrass scenario relative to unmanaged pasture. Energy security could also improve under the corn production scenario if a portion of the corn were converted to ethanol.

External Trade

According to the 2012 U.S. Agricultural Census, a total of 232 farmers within the 13 counties surrounding Vonore produced a mean corn yield of 7156 kg/ha (114 bushels/acre) across 6952 ha (17,178 acres) from 2007 to 2013. While there is a large demand in the region for corn, largely a result of a corn syrup and corn ethanol industry located in the study region, this area is grain deficit. About one million dollars in grains are exported out of the region (IMPLAN 2010 data). Switchgrass is a lightweight, bulky material that does not currently leave the local area due to the high cost of transportation and current lack of a commercial cellulosic ethanol market. (If the regional cellulosic biofuels industry were to grow, however, switchgrass might eventually be exported out of the local area in pelletized form.) Unmanaged pasture is used for on-farm grazing of cows. Therefore, the corn scenario shows high external trade relative to no external trade for the switchgrass and pasture scenarios.

Profitability

Bansal et al. (2013) calculate that the Tennessee production of an average of 18.4 MT/ha (8.23 tons/acre) of switchgrass generates gross revenue of $739/ha ($299/acre), and they project a net profit of $230/ha ($93/acre) within 25 years as conversion efficiencies increase. Based on a price of $77/MT at the biorefinery gate, Yu et al. (December 18, 2013 presentation by Yu TE, Fu JS, English BC, Larson JA to the US DOE on “Air Quality Impacts of Feedstock Transportation for Cellulosic Biofuel Production: A Case Study in Tennessee”) allocate the total estimated cost of switchgrass as 3% opportunity cost, 19% production cost, 49% harvesting cost, 6% storage cost, and 23% transportation cost.

Vonore-area switchgrass received an average of $78.52/MT, which was lower than the average corn price of $198.43/MT during the life of the experiment. However, local corn prices can be highly variable due to weather and external market conditions. And, the assumption that unmanaged pasture would be used as cattle forage meant an avoided hay expenditure of $100.08/MT (Table 1) rather than direct earnings. Therefore, we ranked both switchgrass and corn as having average profitability and unmanaged pasture as having low profitability (Table 7).

MULTIMETRIC EVALUATION

Context-specific qualitative ratings expressing high, low and intermediate sustainability were assigned to each available environmental and socioeconomic sustainability indicator for the Vonore switchgrass-to-ethanol production system relative to two alternative scenarios (Table 1). Environmental sustainability indicator ratings for all three agricultural scenarios are presented in Table 5, social sustainability indicator ratings are presented in Table 6, and economic sustainability indicator ratings are presented in Table 7.

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 based on combination of empirical data, modeling results, and literature review synthesized through expert opinion using the modified Delphi technique described earlier. 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.

The use of this methodology avoided giving preference to (e.g., weighting) any of the sustainability indicators or categories preference within the overall sustainability determination.

The only exception to this general utility function occurred for “profitability” within the Economic category of indicators (Table 7). Based on the local context, the team decided to combine the recommended ROI and NPV indicators (Dale et al. 2013) into an overall measure of economic return (high, medium or low) and to add to this 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 highly variable profits were not considered enough of a negative to turn the average returns into a low profitability trajectory for the corn.

RESULTS OF MULTIMETRIC EVALUATION

For this case study, enough information was available to assign qualitative ratings to 28 of the 35 recommended environmental and socioeconomic sustainability indicators (McBride et al. 2011, Dale et al. 2013) and therefore all 12 of the recommended sustainability categories. A comparison of the 12 environmental and socioeconomic sustainability category ratings generated by MADSS for each of the three scenarios is shown in Figure 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 non-native crop profitable. A rollup of the sustainability category ratings (Table 8) shows that no-till switchgrass and unmanaged pasture both achieved “high environmental sustainability” ratings relative to tilled corn’s “low environmental sustainability” rating.

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’ (since 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 wellbeing’. 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 8).

MADSS 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 8 and Figure 5. Overall sustainability determinations for each of the three scenarios were based on underlying qualitative ratings for environmental sustainability indicators (Table 5), social sustainability indicators (Table 6), and economic sustainability indicators (Table 7), 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 AND CONCLUSION

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 8). This rating was due to the strong influences of intermediate price returns and a lack of external trade (Table 7). Corn production showed a positive economic sustainability rating in spite of its high variability and average returns (Table 7). 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 6), as strongly influenced by high levels of stakeholder involvement unique to this demonstration project owing to its 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 U.S. This was a demonstration project funded by the State of Tennessee. Farmers were awarded contracts at an incentivized rate while the biorefinery was under construction, thereby ensuring an adequate supply of switchgrass by the time the biorefinery came on line (it takes three years for perennial switchgrass to achieve its full yield potential). 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 datasets 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). Despite the fact that 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 thee 35 recommended indicators (McBride et al. 2011, Dale et al. 2013). The available datasets 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, which included everything from point source data related to the biomass processing facility, to field scale analysis of soil quality and fertilizer management regimes as well as harvesting operations, to catchment- and watershed-level examination of sediment and nutrient and herbicide runoff, to the eleven-county road network traversed by diesel trucks emitting air pollutants as they haul biomass to the biorefinery, to the regional scale trade volumes, to national -level fuel price volatility. In spite of these complicating factors, the use of available datasets (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 with 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 one 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 US 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. Thank you to Gina Busby of ORNL for cross-checking our reference list.

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.

Behrman, K. D., J. R. Kiniry, M. Winchell, T. E. Juenger, and T. H. Keitt. 2013. Spatial forecasting of switchgrass productivity under current and future climate change scenarios. Ecological Applications 23: 73-85.

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.

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.

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.

Daystar, J., R. Gonzalez, C. Reeb, R. Venditti, T. Treasure, R. Abt, and S. Kelley. 2014. Economics, environmental impacts, and supply chain analysis of cellulosic biomass for biofuels in the Southern US: Pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum. BioResources 9: 393-444.

Dodds, W. K., W. Bouska, J. L. Eitzmann, T. J. Pilger, K. L. Pitts, A. J. Riley, et al. 2009. Eutrophication of US freshwaters: Analysis of potential economic damages. Environmental Science and Technology 43: 12–19.

Duke, S. O., and S. B. Powles. 2008. Glyphosate: a once-in-a-century herbicide. Pest Management Science 64:319-325.

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.

Einheuser, M. D., A. P. Nejadhashemi, and S. A. Woznicki. 2013. Simulating stream health sensitivity to landscape changes due to bioenergy crops expansion. Biomass and Bioenergy 58: 198-209.

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: 138485.

Epplin, F. M., C. D. Clark, R. K. Roberts, and S. Hwang. 2007. Challenges of the development of a dedicated energy crop. American Journal of Agricultural Economics 98: 1296-1302.

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.

Fox, J. E. 2010. Intent to Continue Growing Switchgrass as a Dedicated Energy Crop: A Case Study of Switchgrass Producers in East Tennessee. Master's Thesis, University of Tennessee. Available online at http://trace.tennessee.edu/utk_gradthes/708

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.

Hayes, J. A. 2014. A Hydrological Analysis of Switchgrass Land Cover in East Tennessee. Master’s Thesis, University of Tennessee.

Jensen, K., C. Clark, P. Ellis, B. English, R. Menard, M. Walsh and D. De La Torre Ugarte. 2007. Farmer willingness to grow switchgrass for energy production. Biomass and Bioenergy 31: 773-781.

Jensen, K., C. Clark, B. English, and R. Menard. 2011. Preferences for marketing arrangements by potential switchgrass growers. Journal of Cooperatives 25: 16-43.

King, J. S., R. Ceulemans, J. M. Albaugh, et al. 2013. The challenge of lignocellulosic bioenergy in a water-limited world. BioScience 63: 102-117.

Kiniry, J. R., Lynd, L., Greene, N., Johnson, M., Casler, M.D., and M. S. Laser. 2008. Biofuels and water use: Comparison of maize and switchgrass and general perspectives. In: Wright, J.H., Evans, D.A., editors. New Research on Biofuels. Nova Science Publishers, Inc. p. 17-30.

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., V. H. Dale, L. M. Baskaran, M. E. Downing, L. M. Eaton, R. A. Efroymson, C. T. Garten, Jr., K. L. Kline, H. I. Jager, P. J. Mulholland, E. S. Parish, P. E. Schweizer, and J. M. Storey. 2011. Indicators to support environmental sustainability of bioenergy systems. Ecological Indicators 11: 1277-1289.

McLaughlin, S. B., and L. A. Kszos. 2005-. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass and Bioenergy 28: 515-535.

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

Mubako, S., and C. Lant. 2008. Water resource requirements of corn-based ethanol. Water Resources Research 44: W00A02.

Mullen, M. D., C. G. Melhorn, D. D. Tyler, and B. N. Duck (1998) Biological and biochemical soil properties in no-till corn with different cover crops. Soil and Water Conservation 53: 219-224.

Parish, E. S., M. Hilliard, L. M. Baskaran, V. H. Dale, N. A. Griffiths, P. J. Mulholland, A. Sorokine, N. A. Thomas, M. E. Downing, and R. Middleton. 2012. Multimetric spatial optimization of switchgrass plantings across a watershed. Biofuels, Bioproducts and Biorefining 6: 58-72.

Pelzer, E., G. Fortino, C. Bockstaller, F. Angevin, C. Lamine, C. Moonen, V. Vasileiadis, D. Guérin, L. Guichard, R. Reau, and A. Messéan. 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, The University of Tennessee. Available online at 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.

Rupp, S. P., L. Bies, A. Glaser, C. Kowaleski, T. McCoy, T. Rentz, S. Riffell, J. Sibbing, J. Verschuyl, and T. Wigley. 2012. Effects of bioenergy production on wildlife and wildlife habitat. Wildlife Society Technical Review 12-03. The Wildlife Society, Bethesda, Maryland, USA.

Soro, L. D. 2011. Impact of Switchgrass Bioenergy Feedstock Production on Soil Carbon Dioxide Flux and Below Ground Soil Organic Carbon Storage in East Tennessee. Master's Thesis, University of Tennessee. Available online at http://trace.tennessee.edu/utk_gradthes/1098

Singh, S. and A. Kumar. 2011. Development of water requirement factors for biomass conversion pathway. Bioresource Technology 102: 1316–1328.

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.

Vasileiadis, V. P., A. C. Moonen, M. Sattin, S. Otto, X. Pons, P. Kudsk, A. Veres, Z. Dorner, R. van der Weide, E. Marraccini, E. Pelzer, F. Angevin, and J. Kiss. 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 7: 045905.

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

Wolf, A. M. and D. E. Baker. 1985. Comparisons of soil test phosphorus by Olsen, Bray P1, Mehlich I and Mehlich III methods. Communications in Soil Science and Plant Analysis 16: 467-484.

Zan, C., J. Fyles, P. Girourard, and R. Samson. 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. Agriculture, Ecosystems & Environment 86: 135-144.

TABLE 1. Three scenarios used to evaluate the sustainability of an East Tennessee dedicated switchgrass-to-ethanol production system. The 2023 ha (5000 acres) of production were scattered across the eleven-county area depicted in Fig. 2.

Parameter	**No-Till Switchgrass**	**Tilled Corn**	**Unmanaged Pasture**
Total Production Area	2023 ha (5000 acres)	2023 ha (5000 acres)	2023 ha (5000 acres)
Timespan of Production	5 years	5 years	5 years
Time of planting	Establish once in spring; no replanting required for at least 10 years	Plant annually	Already established
Tillage Type	No-till method with a drill is preferred for initial establishment	Planted conventionally into a prepared seedbed	No need for replanting
Harvesting equipment	Conventional hay equipment	Combine	Harvest 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 a year (October)	Continuous
Storage	Round bale tarped	Trucked off farm	None
Herbicide Application	1-3 applications of glyphosate herbicide prior to planting (with more applications required for land under conversion from pasture/hay); no further treatment required after establishment. Reed (2012) found that Vonore farmers applied an average of 0.045 kg (0.10 lbs) of herbicide per ton of switchgrass produced.	Annual application of glyphosate herbicide	No herbicide used

Parameter	**No-Till Switchgrass**	**Tilled Corn**	**Unmanaged Pasture**
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 less than 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.	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[3]
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/year (50 million gallon/year) Biorefinery within a one-hour's 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

TABLE 2. Average annual corn grain production for the Vonore, Tennessee area (Fig. 2) compared to the U.S. national average. These U.S. Department of Agriculture (USDA) census data were obtained from the USDA National Agricultural Statistics Service at http://quickstats.nass.usda.gov/ in the reported units of bushels per acre. Each bu/acre of corn was converted to 62.77 kg/ha of corn per Iowa State University's conversion factors (http://www.extension.iastate.edu/agdm/wholefarm/html/c6-80.html). The 11 Tennessee counties included in the Vonore-area averages were Anderson, Blount, Bradley, Hamilton, Loudon, McMinn, Meigs, Monroe Polk, Rhea, and Roane.

Year of Census	Vonore-area average corn grain yield		U.S. national average corn grain yield		Percent difference in regional versus national average annual corn grain yield
	bu/acre	kg/acre	bu/acre	kg/ha	
1997	72.5	4,549	126.7	7,953	43%
2002	87.9	5,517	129.3	8,116	32%
2007	76.1	4,777	150.7	9,459	50%
2012	76.9	4,824	123.1	7,727	38%

TABLE 3. Environmental sustainability indicators [19 indicators in 6 categories based on McBride et al. (2011)] evaluated for the feedstock and logistics portions of an East Tennessee switchgrass-to-ethanol demonstration-scale production system. Sources and assumptions used to generate case-study indicator values are discussed within the text. The qualitative ratings were used to assess the indicator attributes within the multi-attribute decision support system (MADSS) developed for comparing no-till switchgrass production to alternative scenarios of tilled corn and unmanaged pasture. The shaded qualitative ratings were those assigned to the no-till switchgrass scenario within the MADSS. 'N/A' means that the rating was not an available option.

Sustainability Indicator Category	**Recommended Social Sustainability Indicator**	**Case Study Indicator Information**	**Potential Sustainability Ratings**		
			Low	**Inter-mediate**	**High**
Soil quality	Total organic carbon (TOC) in Mg/ha	38 Mg/ha at depth of 15-20 cm (6-8 in.) after 3 years 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	No information available	N/A	N/A	N/A
	Extractable phosphorus (P) in Mg/ha	0 to 0.06 Mg/ha at depth of 15-20 cm (6-8 in.) averaged over 3 years (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 = 220)	low bulk density OR high bulk density	non-restrictive bulk density	N/A

Water quality & quantity	Nitrate concentration in streams in mg/L and as export in kg/ha/year	Export of 0.36 kg/ha/yr measured at Thompson farm; 0.15 mg/L modeled in Lenoir City catchment	increasing nitrate concentrations/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/year	Export of 0.13 kg/ha/yr measured at Thompson farm; 0.11 mg/L modeled in Lenoir City catchment	increasing P concentrations/export	no change in P concentrations/export	decreasing P concentrations/export
	Suspended sediment concentration in streams as mg/L and as export in kg/ha/year	Export of 0.86 kg/ha/year measured at Thompson farm; 66 mg/L modeled in Lenoir City catchment	increasing sediment concentrations	no change in sediment concentrations	decreasing sediment concentrations
	Herbicide concentration in streams as mg/L and export in kg/ha/year	~1406 kg (one-time total) of glyphosate applied to 2023 ha of production spread across an 11-county area	multiple herbicide applications	herbicide applied during establishment only	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 baseflow	increasing baseflow

	Consumptive water use (incorporates base flow) as m^3/ha/day	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 less than 2.5 m diameter ($PM_{2.5}$) in µg/m^3	0.209 MT/year (combined field operations, transportation and handling)	higher PM emissions	average PM emissions	lower PM emissions
	Total particulate matter less than 10 m diameter (PM_{10}) in µg/m^3	0.037 MT/year (combined field operations, transportation and handling)			
Productivity	Aboveground net primary productivity (ANPP)/yield in g C/m^2/year	394.5 g C/m^2/year 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	some 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/year 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

TABLE 4. Social and economic sustainability indicators [16 indicators in six categories based on Dale et al. (2013)] evaluated for the feedstock and logistics portions of an East Tennessee switchgrass-to-ethanol demonstration-scale production system. Sources and assumptions used to generate case-study indicator values are discussed within the text. The qualitative ratings were used to assess the indicator attribute within the multi-attribute decision support system (MADSS) developed for comparing no-till switchgrass production to alternative scenarios of tilled corn and unmanaged pasture. The shaded qualitative ratings were those assigned to the no-till switchgrass scenario within the MADSS. 'N/A' means that the rating was not an available option.

Sustainability Indicator Category	**Recommended Social Sustainability Indicator**	**Case Study Indicator Information**	**Potential Sustainability Ratings**		
			Low	**Inter-mediate**	**High**
Social well-being	Employment as # of FTE jobs	Creation of 67-96 jobs within the 13 counties surrounding the biorefinery	fewer jobs	no change in jobs	more jobs
	Household income as $/day	Additional income since November harvest occurs at a time when there is no other local agricultural work available	less household income	some household income	more household income
	Work days lost due to injury as average # work days lost/worker/year	Genera has recorded 0 incidents for switchgrass harvesting and preprocessing operations for over 1325 days	increase in work days lost	average work days lost	decrease in work days lost
	Food security as % change in food price volatility	0% change	increasing food price volatility	no noticeable change in food price	decreasing food price volatility

				volatility	
Resource conservation	Depletion of non-renewable energy resources as amount of petroleum extracted per year (MT)	Over 2 million gallons of gasoline replaced by local ethanol (annually), keeping $5.1-$5.8M 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’s 2012 national assessment)			
Social acceptability	Public opinion as percent favorable opinion	55% of TN farmers responded favorably in 2009 to growing switchgrass & 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% since all switchgrass producers were required to meet with Extension agents and there were a variety of	low stakeholder engagement	average stakeholder involvement	high stakeholder engagement
	Effective stakeholder participation as percent of documented responses				

	addressing stakeholder concerns and suggestions (reported on an annual basis)	surveys, public meetings and focus groups			
	Risk of catastrophe as annual probability of catastrophic event	1 arson event in 5 years 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 one year	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	no 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 years (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 [note that this indicator was not included in the list of socioeconomic indicators proposed by Dale et al. (2013)]	Switchgrass yields and prices were unaffected by weather events, pests, or external market conditions	highly variable profit	N/A	low profit variability

1107

TABLE 5. Environmental sustainability evaluation of three alternative agricultural scenarios for East Tennessee based on a combination of empirical data, modeling results and literature synthesized through expert opinion. Bolding and italics of qualitative attribute ratings indicates ***high sustainability***, **low sustainability**, and intermediate sustainability.

	No-Till Switchgrass Scenario	**Unmanaged Pasture Scenario**	**Tilled Corn Scenario**
ENVIRONMENTAL SUSTAINABILITY	***High***	***High***	**Low**
├─***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**	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 TOC***	no change in soil TOC	**decreasing soil TOC**
├─Phosphorus.	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	***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 baseflow	no change in baseflow	no change in baseflow
└─*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	***lower CO emissions***	***lower CO emissions***	average CO emissions
└─Particulate Matter	***lower PM emissions***	***lower PM emissions***	average PM emissions

TABLE 6. Social sustainability evaluation of three agricultural scenarios for East Tennessee based on a combination of empirical data, modeling results and literature synthesized through expert opinion. Bolding and italics of qualitative attribute ratings indicates ***high sustainability***, **low sustainability**, and intermediate sustainability.

	No-Till Switchgrass Scenario	**Unmanaged Pasture Scenario**	**Tilled Corn Scenario**
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

TABLE 7. Economic sustainability evaluation of three agricultural scenarios for East Tennessee based on a combination of empirical data, modeling results and literature synthesized through expert opinion. Bolding and italics of qualitative attribute ratings indicates ***high sustainability***, **low sustainability**, and intermediate sustainability.

	No-Till Switchgrass Scenario	Unmanaged Pasture Scenario	Tilled Corn Scenario
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
├─ROI & NPV	average returns	**low returns**	average returns
└─Variability	***low variability***	***low variability***	**highly variable**
└─**External Trade**	no external trade	no external trade	***high external trade***

TABLE 8. Results of a multi-attribute decision support system (MADSS) sustainability evaluation of three alternative agricultural scenarios for East Tennessee (Table 1). The underlying qualitative sustainability ratings are based on a combination of empirical data, modeling results and literature synthesized through expert opinion.

	No-Till Switchgrass Scenario	Unmanaged Pasture Scenario	Tilled Corn Scenario
Overall Sustainability	High	Intermediate	Intermediate
Environmental Sustainability	High	High	Low
Economic Sustainability	Intermediate	Low	High
Social Sustainability	High	Intermediate	Intermediate

FIGURE LEGENDS

FIG. 1. Applicability of 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.

FIG. 2. (a) Fuelshed location of Vonore switchgrass experiment in East Tennessee, which included Tennessee farms within 80 km (50 miles), i.e., approximately a one-hour's drive, of the Vonore demonstration-scale biorefinery. The State of Tennessee is located in the southeastern United States. (b) Distribution of the 2064 ha (5100 acres) of switchgrass throughout 11 East Tennessee counties at the peak of production in 2010.

FIG. 3. Aggregation hierarchy of 12 categories of sustainability indicators within a Multi Attribute 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 identified by derived from McBride et al. (2011) and Dale et al. (2013).

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. Each category value represents an aggregation of individual sustainability indicator values.

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 rating, and the outer edges represent the highest possible rating for the three scenarios.

Figure 1

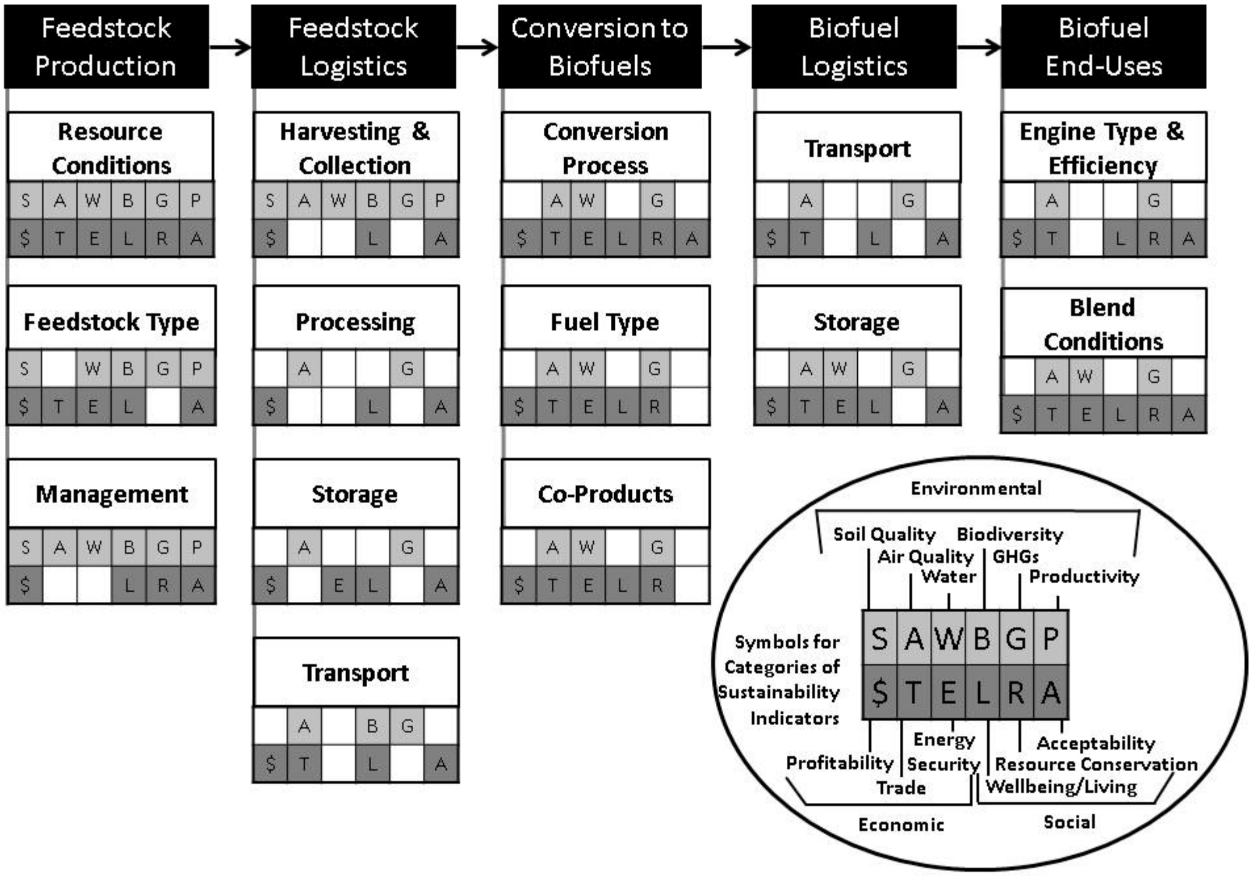

Feedstock Production
Feedstock Logistics
Conversion to Biofuels
Biofuel Logistics
Biofuel End-Uses
Resource Conditions
S A W B G P
$ T E L R A
Feedstock Type
S W B G P
$ T E L A
Management
S A W B G P
$ L R A
Harvesting & Collection
S A W B G P
$ L A
Processing
A G
$ L A
Storage
A G
$ E L A
Transport
A B G
$ T L A
Conversion Process
A W G
$ T E L R A
Fuel Type
A W G
$ T E L R
Co-Products
A W G
$ T E L R
Transport
A G
$ T L A
Storage
A W G
$ T E L A
Engine Type & Efficiency
A G
$ T L R A
Blend Conditions
A W G
$ T E L R A
Environmental
Soil Quality
Biodiversity
Air Quality
GHGs
Water
Productivity
Symbols for Categories of Sustainability Indicators
S A W B G P
$ T E L R A
Energy
Acceptability
Profitability
Security
Resource Conservation
Trade
Wellbeing/Living
Economic
Social

Figure 2

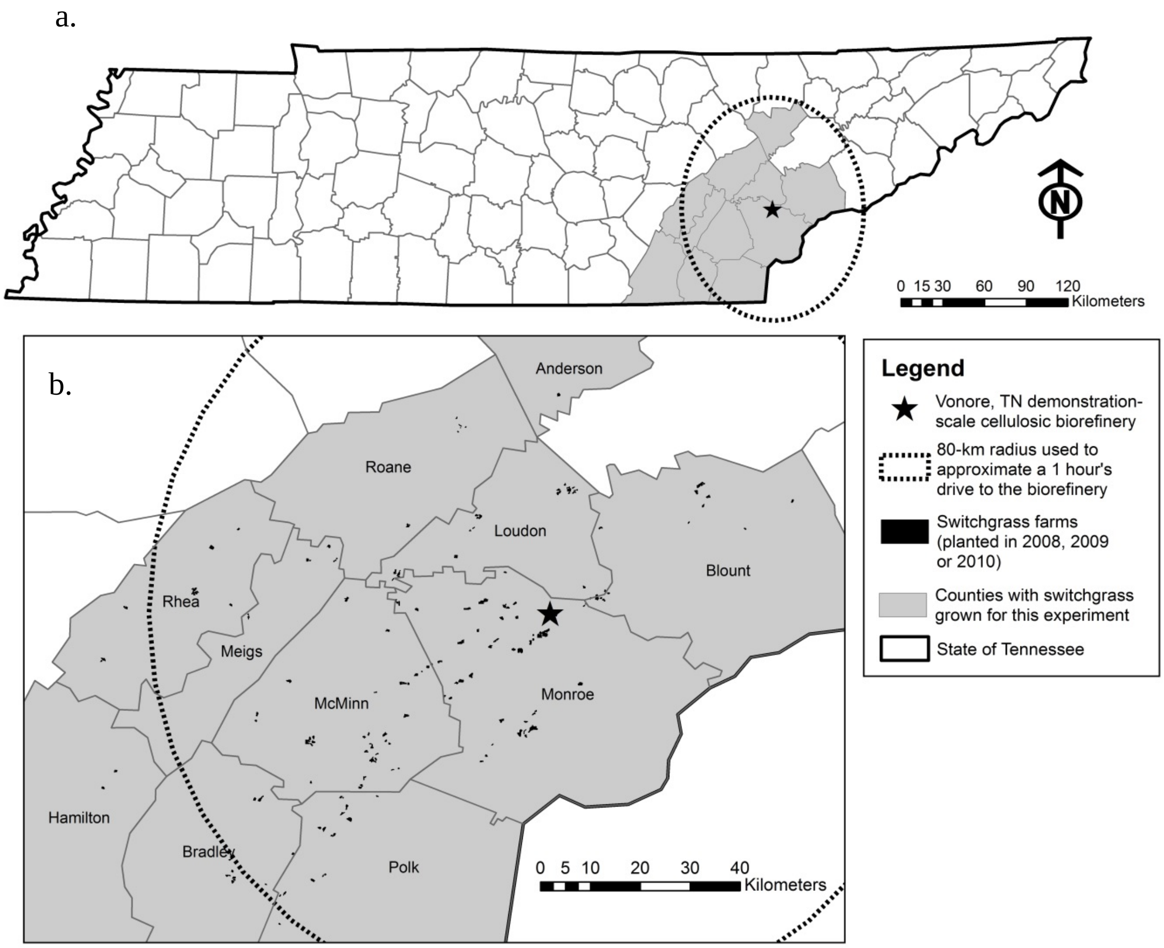

a.
0 15 30 60 90 120
Kilometers
N
b.
Anderson
Roane
Loudon
Blount
Rhea
Meigs
McMinn
Monroe
Hamilton
Bradley
Polk
0 5 10 20 30 40
Kilometers
Legend
Vonore, TN demonstration-scale cellulosic biorefinery
80-km radius used to approximate a 1 hour's drive to the biorefinery
Switchgrass farms (planted in 2008, 2009 or 2010)
Counties with switchgrass grown for this experiment
State of Tennessee

Figure 3

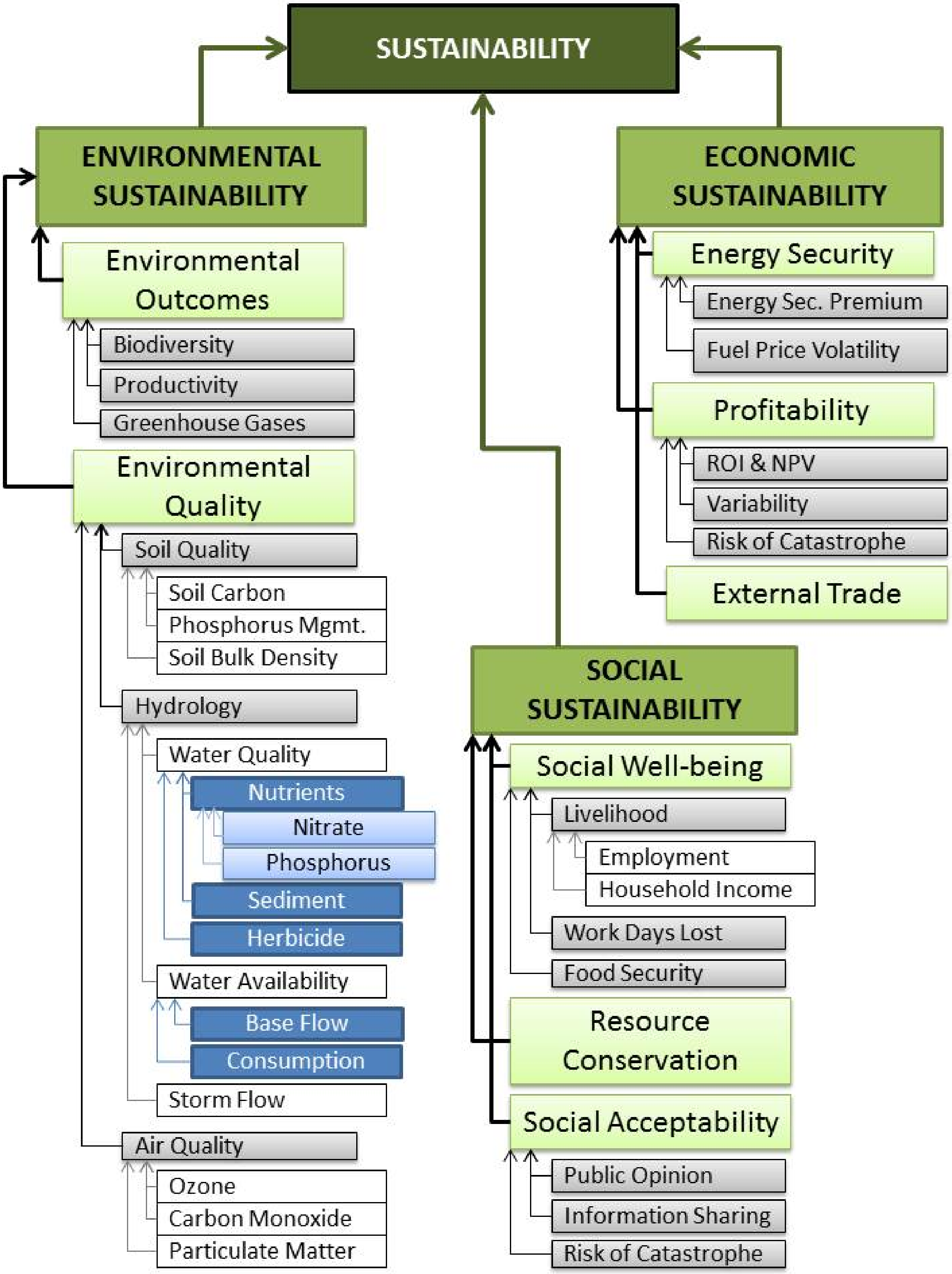

SUSTAINABILITY
ENVIRONMENTAL SUSTAINABILITY
Environmental Outcomes
Biodiversity
Productivity
Greenhouse Gases
Environmental Quality
Soil Quality
Soil Carbon
Phosphorus Mgmt.
Soil Bulk Density
Hydrology
Water Quality
Nutrients
Nitrate
Phosphorus
Sediment
Herbicide
Water Availability
Base Flow
Consumption
Storm Flow
Air Quality
Ozone
Carbon Monoxide
Particulate Matter
ECONOMIC SUSTAINABILITY
Energy Security
Energy Sec. Premium
Fuel Price Volatility
Profitability
ROI & NPV
Variability
Risk of Catastrophe
External Trade
SOCIAL SUSTAINABILITY
Social Well-being
Livelihood
Employment
Household Income
Work Days Lost
Food Security
Resource Conservation
Social Acceptability
Public Opinion
Information Sharing
Risk of Catastrophe

Figure 4

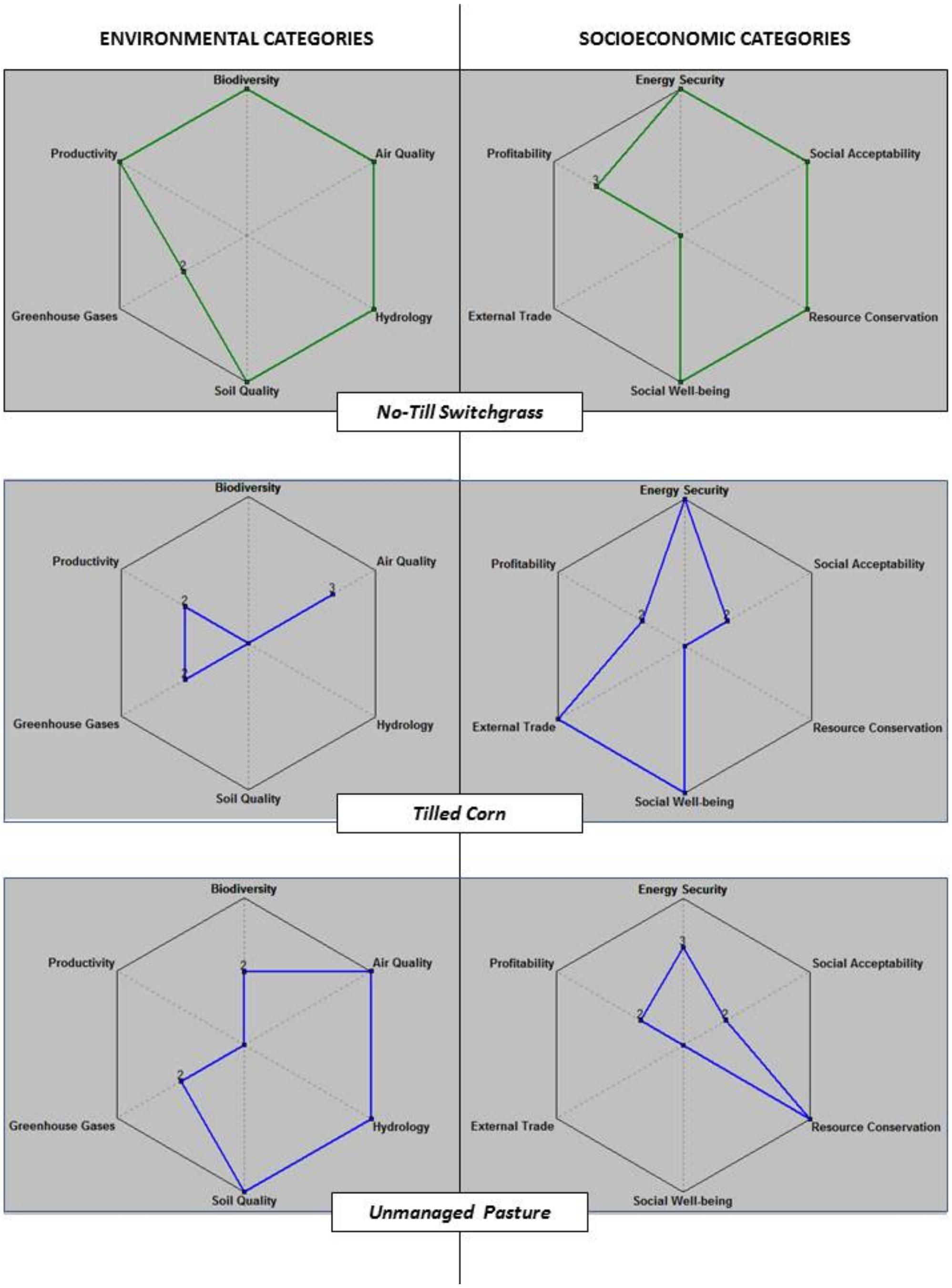
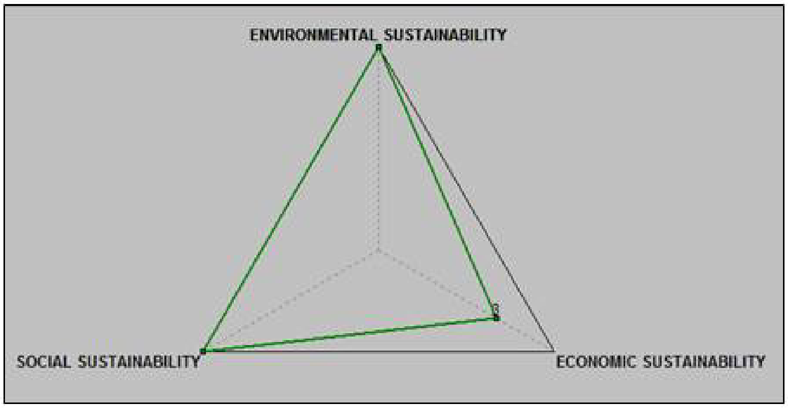
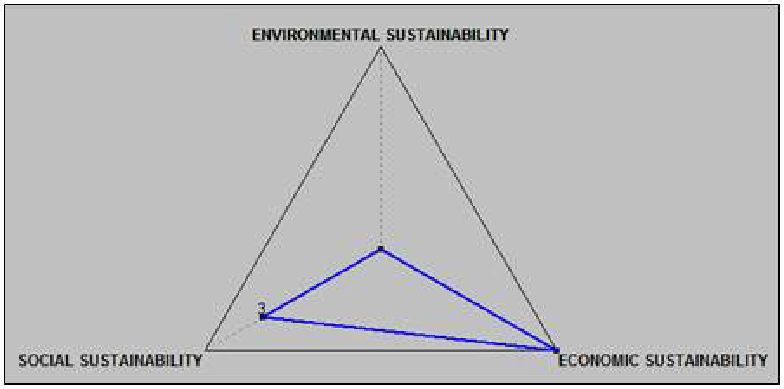

ENVIRONMENTAL CATEGORIES
SOCIOECONOMIC CATEGORIES
Biodiversity
Air Quality
Hydrology
Soil Quality
Greenhouse Gases
Productivity
2
Energy Security
Social Acceptability
Resource Conservation
Social Well-being
External Trade
Profitability
3
No-Till Switchgrass
Biodiversity
Air Quality
Hydrology
Soil Quality
Greenhouse Gases
Productivity
2
2
3
Energy Security
Social Acceptability
Resource Conservation
Social Well-being
External Trade
Profitability
2
2
Tilled Corn
Biodiversity
Air Quality
Hydrology
Soil Quality
Greenhouse Gases
Productivity
2
2
Energy Security
Social Acceptability
Resource Conservation
Social Well-being
External Trade
Profitability
3
2
2
Unmanaged Pasture

Figure 5

No-Till Switchgrass



Tilled Corn



Unmanaged Pasture