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Multimetric spatial optimization of switchgrass plantings across a watershed†

Esther S. Parish, Michael R. Hilliard, Latha M. Baskaran, Virginia H. Dale, Natalie A. Griffiths, Patrick J. Mulholland, Alexandre Sorokine, Neil A. Thomas, and Mark E. Downing, Oak Ridge National Laboratory, TN, USA
Richard S. Middleton, Los Alamos National Laboratory, NM, USA

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Abstract: The increasing demand for bioenergy crops presents our society with the opportunity to design more sustainable landscapes. We have created a Biomass Location for Optimal Sustainability Model (BLOSM) to test the hypothesis that landscape design of cellulosic bioenergy crop plantings may simultaneously improve water quality (i.e. decrease concentrations of sediment, total phosphorus, and total nitrogen) and increase profits for farmer-producers while achieving a feedstock-production goal. BLOSM was run using six scenarios to identify switchgrass (*Panicum virgatum*) planting locations that might supply a commercial-scale biorefinery planned for the Lower Little Tennessee (LLT) watershed. Each scenario sought to achieve different sustainability goals: improving water quality through reduced nitrogen, phosphorus, or sediment concentrations; maximizing profit; a balance of these conditions; or a balance of these conditions with the additional constraint of converting no more than 25% of agricultural land. Scenario results were compared to a baseline case of no land-use conversion. BLOSM results indicate that a combined economic and environmental optimization approach can achieve multiple objectives simultaneously when a small proportion (1.3%) of the LLT watershed is planted with perennial switchgrass. The multimetric optimization approach described here can be used as a research tool to consider bioenergy plantings for other feedstocks, sustainability criteria, and regions. Published in 2012 by John Wiley & Sons, Ltd

Keywords: economics; landscape design; sustainability; switchgrass; Tennessee; water quality

Introduction

Sustainable production of bioenergy crops for liquid transportation fuel will require a comprehensive understanding of environmental and socio-economic factors and interactions between those factors at the regional scale.[1] When bioenergy systems are implemented in an appropriate way for the particular situation, several types of benefits can be achieved.[2] Potential environmental benefits

Correspondence to: Esther S. Parish, Center for BioEnergy Sustainability, Oak Ridge National Laboratory, One Bethel Valley Road, PO Box 2008, MS-6036, Oak Ridge, TN 37831-6036, USA. E-mail: parishes@ornl.gov

include decreased greenhouse gas (GHG) emissions,[3] enhanced habitats for wildlife,[4] reduced erosion, improved soil and water quality,[5] regional cooling,[6] ecosystem services like pollination and pest suppression,[7] and more stable global land use reducing pressure to clear more land.[8] Potential socio-economic benefits include diversified fuel supplies, improved energy security, and increased rural employment.[9] Although an in-depth analysis of sustainability of biofuel production would test potential trade-offs among all of these environmental and socio-economic factors, there are no tools yet available to conduct such a comprehensive evaluation across the entire biofuel supply chain. As a first step toward holistic understanding of a complex agro-economic system at a regional scale, this analysis focuses on the intersection of feedstock production, farm profits, and water quality.

In future years, most of the new contributions to biofuel production in the United States will come from second-generation biofuels derived from cellulosic feedstocks, such as perennial grasses, short-rotation trees, and crop residues.[10] We hypothesize that these cellulosic crops can be planted according to a landscape design so that the shift in land use may positively affect water quality in and downstream of watersheds used for bioenergy crop production, particularly in terms of nitrogen, phosphorous, and sediment runoff. By landscape design, we mean that the choice of crop type, location, and management focuses on a set of sustainability goals for the watershed or region, such as the simultaneous realization of: (i) achieving the necessary feedstock production quantity, (ii) ensuring farm profits, and (iii) improving water quality. We have developed the Biomass Location for Optimal Sustainability Model (BLOSM) as a research tool to test this hypothesis. Our long-term goal is to use this multimetric modeling approach to improve understanding of interactions and trade-offs among other environmental and socio-economic factors contributing to bioenergy sustainability.

Multimetric modeling approach

The BLOSM model enables us to integrate outputs from a hydrologic model and an economic model to allow consideration of watershed-level trade-offs resulting from various bioenergy crop-production configurations across a landscape. In this analysis, we consider farm profits and water quality given constraints on the amount of land-use change and the target amount of perennial switchgrass (*Panicum virgatum*) feedstock that may be needed for a nearby commercial-scale (190 million liter per year) ethanol production facility planned for East Tennessee. BLOSM results are spatially explicit because each land-use-change projection is tied to particular locations within the watershed that exhibit unique combinations of physiographic parameters (e.g. slope, soil type, and current land cover). However, BLOSM results are not tied to specific farm locations or land owners and should therefore not be seen as prescriptive.

In this analysis, we use BLOSM to explore six land-use-conversion scenarios (Table 1) designed to achieve different environmental and socio-economic criteria, both singly and in combination, as compared to a baseline case of no land-use conversion. Each scenario is intended to result in the production of 58 967 metric tonnes per year (65 000 tons/year) of switchgrass from the 2726 km^2 (674 000 acre) Lower

Table 1. Six land-use conversion scenarios run with the Biomass Location for Optimal Sustainability Model (BLOSM) to explore opportunities for producing a target quantity of switchgrass within the Lower Little Tennessee (LLT) watershed.

Scenario	Description
1. Minimize Nitrogen	Minimize concentrations of total nitrogen (i.e. the sum of organic nitrogen, nitrate, nitrite, and ammonium) at the outlet of the LLT watershed.
2. Minimize Phosphorus	Minimize concentrations of total phosphorus (i.e. the sum of organic and inorganic phosphorus) at the outlet of the LLT watershed.
3. Minimize Sediment	Minimize concentrations of total suspended sediments at the outlet of the LLT watershed.
4. Maximize Profit	Maximize total economic profit from land conversion to switchgrass throughout the LLT watershed.
5. Balanced Objectives	Achieve all three water-quality objectives (Scenarios 1–3) to the extent possible while also maximizing economic profit (Scenario 4) to the extent possible, thus achieving a ‘Balanced’ solution.
6. Limit Agricultural Land Conversion	Run the ‘Balanced’ solution (Scenario 5) with the additional constraint that no more than 25% of the land-area conversion can occur at the expense of cropland.

Little Tennessee (LLT) watershed (Fig. 1), an area that straddles Tennessee and North Carolina. While 75% of the watershed is forested and occupied by portions of the Cherokee National Forest and other federal lands, pasture/hayland (12%) and agricultural land (2%) comprising traditional row crops such as corn and soybeans occur in the downstream (northwestern) portion of the watershed. For this analysis, we only allow land currently designated as agricultural land or pasture/hayland to be converted to switchgrass.

Our first four scenarios (Table 1) – Minimize Nitrogen, Minimize Phosphorus, Minimize Sediment, and Maximize Profit – are analyzed as single objectives. These four scenario runs establish the potential improvement in the individual metrics one at a time while converting enough acres of land to achieve the production goal. The potential extreme for each of the metrics provides a uniform scale for comparison, namely the 'percent of maximum achievable'. The fifth scenario – Balanced Objectives – seeks to achieve all three of the water-quality objectives to the extent possible while also maximizing economic profit and meeting the production goal. The sixth scenario – Limit Agricultural Land Conversion – tests the effects of meeting all of the objectives to the extent possible while adding the additional constraint of limiting agricultural land conversion to 25% [10] of the total land available (and thereby forcing more of the pasture/hayland to be converted to switchgrass).

Data and methods

BLOSM operates on a geographic information system (GIS)-based regional data set and uses measures of land-use change, economic profitability, and subbasin-level effects of incorporating biomass plantings to determine the

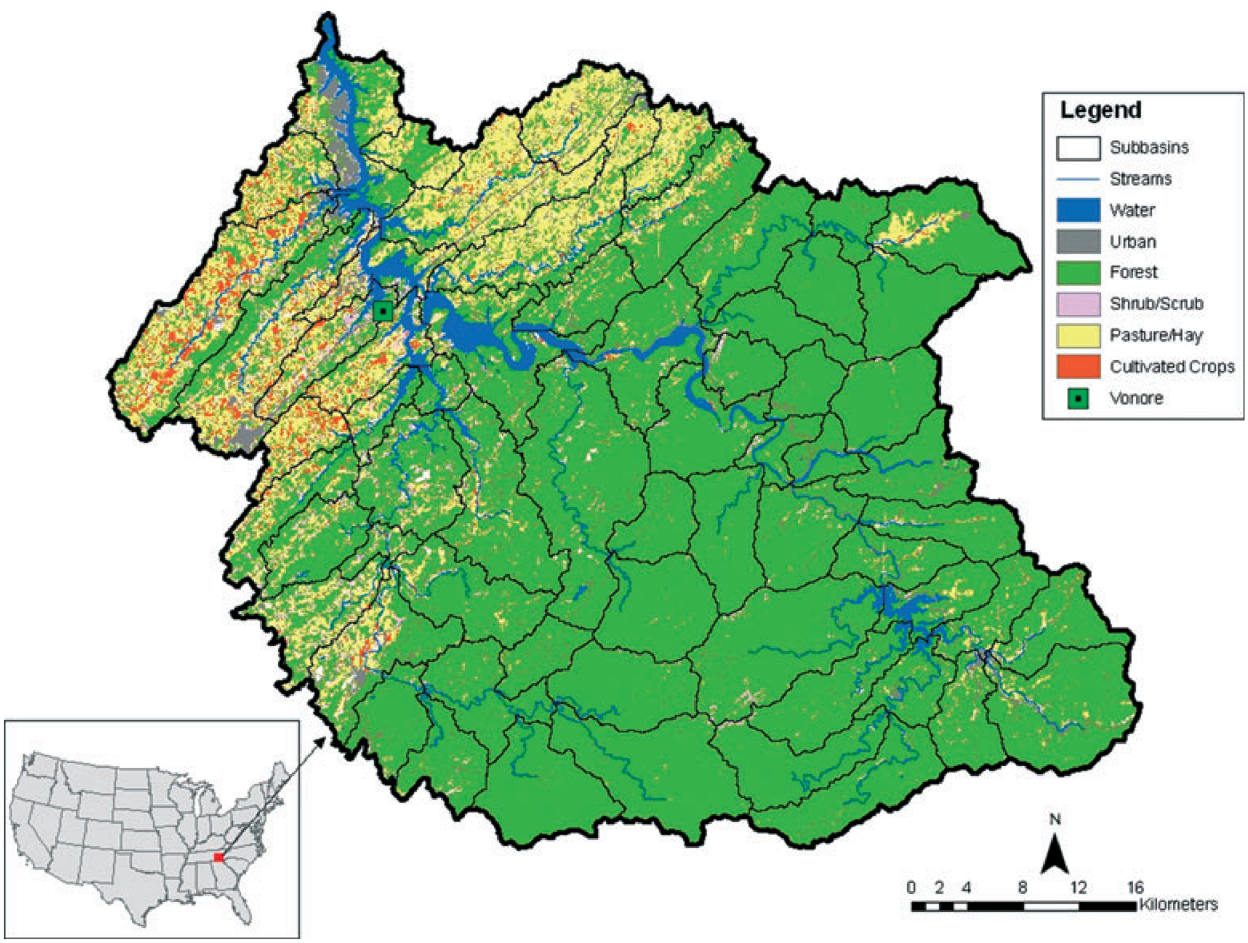


Figure 1. Baseline land cover and stream network in the Lower Little Tennessee watershed (based on the 2011 National Land Cover Dataset). A demonstration-scale cellulosic ethanol plant has been built in Vonore, TN, and a nearby commercial-scale facility is planned for construction by 2014.

sustainability of any potential planting of biomass crops.[11] As shown in Fig. 2, BLOSM results are based on a variety of data inputs, including: water-quality results from a version of the Soil and Water Assessment Tool (SWAT)[12] hydrologic model that has been parameterized for perennial switchgrass growth and management, and modified to run in a parallel computing environment; subbasin-level projected switchgrass yields calculated from an empirical grid of US switchgrass yields;[13] crop-yield projections and economic data derived from the Policy Analysis System (POLYSYS),[14] a national economic model; and, local crop budget data supplied by the University of Tennessee Institute of Agriculture (UTIA). The land-use-change solutions resulting from BLOSM runs may be visually explored and analyzed with ArcGIS software. The water-quality modeling, economic profit modeling, and optimization modeling components of BLOSM are discussed in separate sections.

Water quality modeling component

Soil erosion and increased nutrient (e.g. nitrogen and phosphorus) concentrations in streams resulting from excessive fertilizer use are among the most important agricultural impacts on water quality.[15] Stream suspended sediment concentration is a good indicator of erosion as well as loss of sediment-bound phosphorus, an important component of phosphorus loss from agricultural fields. Excess nutrients can have widespread ecological impacts on streams, rivers, and downstream aquatic systems, potentially contributing to habitat loss,[16] eutrophication, or hypoxia.[17–20] Thus, stream sediment and nutrient concentrations can reflect agricultural practices occurring on the land and can be indicative of the potential biological impacts that agriculture can have on aquatic ecosystems.[21]

BLOSM's water-quality projections are based on data produced by SWAT,[12] a physically based watershed-scale

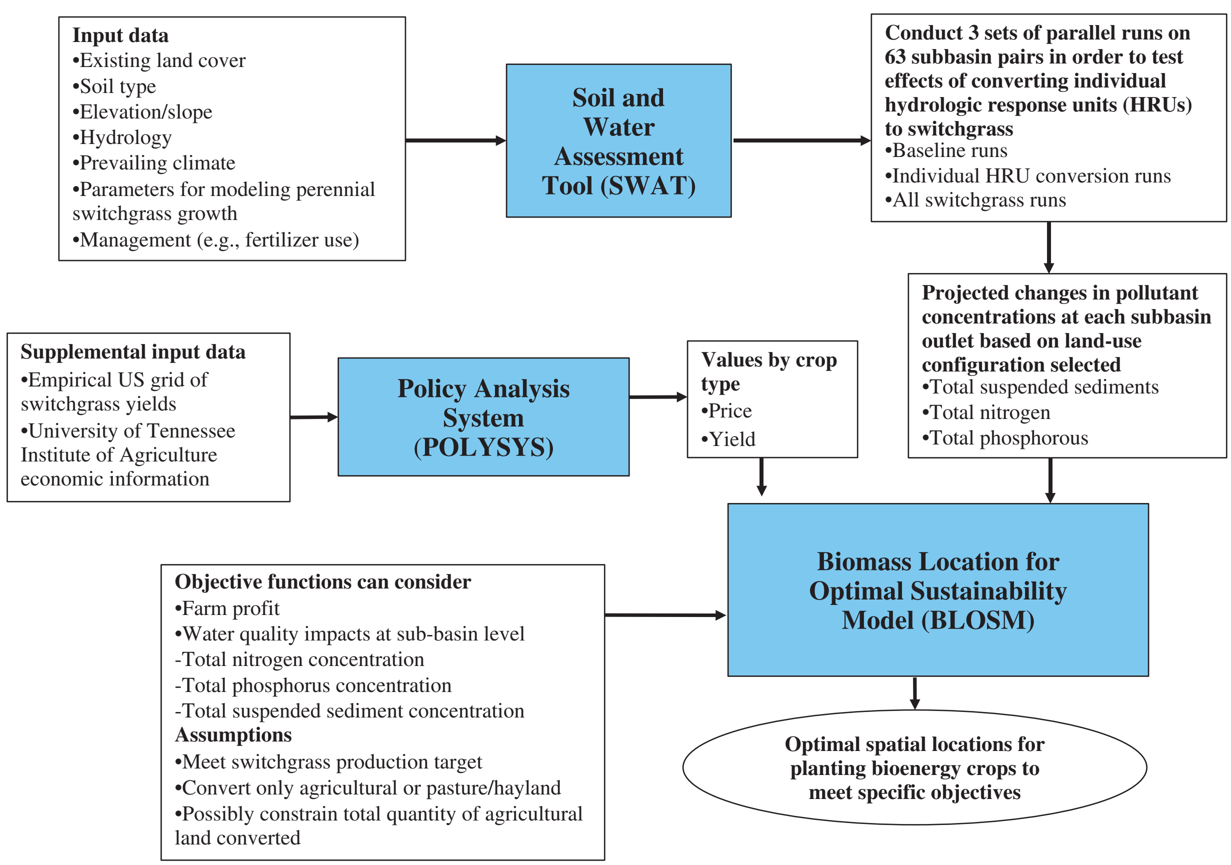
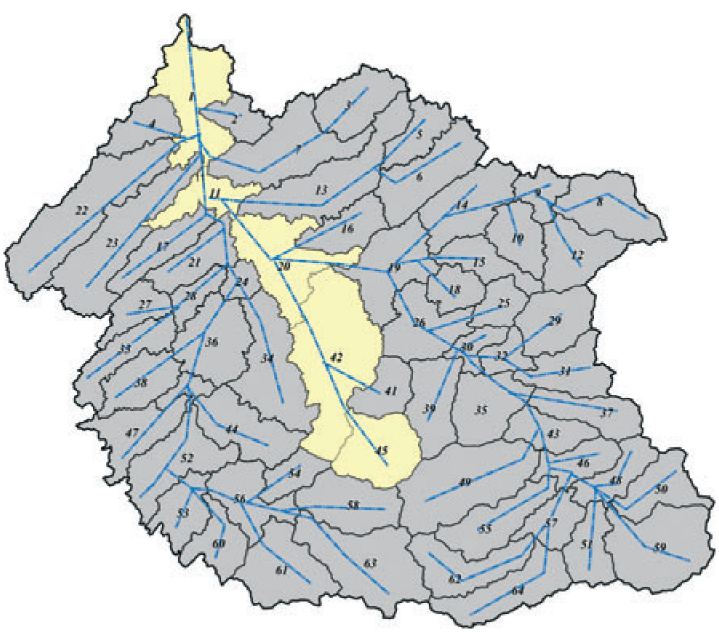


Figure 2. Interface among the hydrologic model (SWAT), the economic model (POLYSYS), and the newly developed Biomass Location for Optimal Sustainability Model (BLOSM). Note that SWAT defines a hydrologic response unit (HRU) to be a unique combination of a land cover, soil, and slope class within a subbasin.

model developed by the US Department of Agriculture and Texas A&M University to predict the impact of land-management practices on flows of water, sediment, and nutrients in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. We have used SWAT to divide the LLT watershed into 64 subbasins (Fig. 3(a)) on the basis of 30-m digital elevation model (DEM) data. These subbasins range from 11 to 111 km^2 with an average size of 43 km^2. The 2001 National Land Cover Dataset (NLCD)[22] has been used in conjunction with the DEM and State Soil Geographic (STATSGO) soil data[23] to produce 6965 hydrologic response units (HRUs) for the LLT watershed. HRUs are unique combinations of land-cover class, soil class, and slope category within each subbasin and are not necessarily contiguous land areas. Based on our decision that only pasture/hayland or agricultural land is likely to be converted to switchgrass within the LLT watershed, only 1054 of the study area HRUs are potentially available, or 'eligible', for switchgrass plantings. These eligible HRUs are concentrated in the downstream portion of the LLT watershed; in fact, five of the forested subbasins in the upper portion of the watershed do not contain any eligible HRUs. The average land area eligible for conversion is 13 ha (31 acres) for an agricultural HRU and 55 ha (136 acres) for a pasture/hayland HRU.

The plant-growth and land-management parameters used in SWAT affect sediment erosion rates and nutrient input to the streams. We have modified the SWAT plant-growth parameters for switchgrass in order to better represent perennial growth on a ten-year cycle (see details in Baskaran

(a) Subbasins and stream flow network used to track flow of pollutants during optimization:



(b) Primary objective function used for optimization:

$$\text{maximize } p\sum_{i=1,}^{H} r_i x_i + \sum_{Q=N,P,S} \frac{w_Q}{B} \sum_{i=1}^{H} \sum_{k=1}^{B} a_{Qik} x_i$$

(c) Variables used in optimization formulation:

Symbol	Description	Units
Q	Water-quality metric; either N (total nitrogen concentration), P (total phosphorus concentration) or S (total suspended sediment concentration)	mg/L
k	Subbasin ID; numbered from 1 to 64, with 1 being the mouth of the entire Lower Little Tennessee watershed	None
b_{Qk}	Baseline value for water-quality metric Q in subbasin k	mg/L
i	Hydrologic response unit (HRU) ID; unique combinations of slope, soil type and current land cover generated by the Soil Water Assessment Tool (SWAT) hydrologic model; numbered from 1 to 6965	None
a_{Qik}	Effect on water-quality metric Q in subbasin k from conversion of HRU i to switchgrass	mg/L
r_i	Expected change in net revenue from converting HRU i to switchgrass; based on outputs from the Policy Analysis System (POLYSYS) economic model	$
x_i	Proportion of HRU i converted to switchgrass; ranges from 0 (no conversion) to 1 (100% of area converted)	None
p	Weight assigned to profit in objective function (assumed to be nonnegative)	None
w_Q	Weight assigned to water-quality metric Q (assumed to be negative)	None
H	Number of HRUs	None
B	Number of subbasins	None
T*	Target tonnage of switchgrass	Tons
t_i	Tons of switchgrass contributed by conversion of HRU i	Tons

Figure 3. Essential components of the Biomass for Optimal Sustainability Model (BLOSM) formulation: (a) Map of the 64 subbasins of the Lower Little Tennessee (LLT) watershed and streamflow network. (b) The primary objective function used for optimization. (c) Explanation of key variables used in the optimization formulation.

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et al.[24]). All other agricultural land within the watershed has been modeled as annual row crops with growth and management protocols similar to those for corn. Pasture/hayland has been modeled on a four-year rotation. Data from actual corn, pasture, and switchgrass plantings in the East Tennessee area have been used to determine the fertilizer-application amounts input into SWAT.

On the basis of these inputs, we first ran the ArcSWAT version of SWAT2005[25] on a desktop to produce annual water-quality results at the outlet of each LLT watershed subbasin over 12 years under climate conditions set by the automatic weather generator. We excluded the first two years of data from all calculations to allow for model spin-up. Data values of nutrient and sediment concentrations (in mg/l) obtained for each subbasin's outlet included the overland component of the specific subbasin as well as in-stream contributions from upstream subbasins. A simplified stream network showing the linkages among the 64 subbasins is shown in Fig. 3(a).

Next we used the input files outside of ArcSWAT to produce parallel runs on a supercomputer so the effects of converting individual HRUs to switchgrass within each subbasin could be tested. We made three sets of parallel runs with the 63 upstream/downstream pairs contained in the LLT watershed:

1. Baseline nutrient and sediment concentrations were calculated at each subbasin outlet based upon the NLCD 2001 land cover dataset. This resulted in 63 paired subbasin runs referred to as the 'Baseline' runs.
2. Projected nutrient and sediment concentrations were calculated for each subbasin and its connected downstream subbasin following the conversion of each individual agricultural or pasture/hayland HRU to switchgrass. This resulted in 1054 paired subbasin runs referred to as the 'Individual HRU Conversion' runs.
3. Projected nutrient and sediment concentrations were calculated for each subbasin and its connected downstream basin based on the conversion of *every* agricultural and pasture land HRU to switchgrass. This resulted in 59 paired subbasin runs referred to as the 'All Switchgrass' runs.

We developed a computer program to coordinate running the 1176 SWAT-based paired subbasin calculations in parallel within a mixed desktop/high-performance-computing environment that used an 80-node cluster with up to 40 nodes allocated for each computation. The output from these three sets of paired runs forms the basis for the water-quality variables used in the BLOSM optimization formulation described later.

Economic profit modeling component

Potential profit from cellulosic energy crops is not yet fully understood and will undoubtedly vary by region. Suggesting a dollar difference in return per acre from switchgrass compared to corn, hay, or pasture depends on understanding management techniques, market security, a contracted sale price, and long-term foregone economic returns (i.e. the opportunity cost of land). Deciding between an annual crop supported by existing farm programs (with subsidies and crop insurance) and an alternative perennial crop is definitely not a straightforward decision. Although uncertainty and risk are inherent in estimating either costs or revenues associated with land-use conversion, the approach taken in this paper is deterministic because risk is beyond the scope of this analysis.

Table 2 shows the comparison of relative net revenues that farmer-producers in the LLT watershed might use to make their planting decisions. Switchgrass cost-of-production estimates for this study are based on 3-year UTIA budgets.[26] For comparison and estimation of expected opportunity costs, all other crop-production budgets have been based on UTIA production budgets.[27]

Regardless of the crop type, the expectation of net revenue is dependent on projected crop yield. With all other

Table 2. Comparison of relative net revenues considered by farmers in the Lower Little Tennessee watershed.

Commodity	Average Yield	Cost	Return	Net Revenue
Corn	75.3 quintals/ha (120 bushels/acre)	$986/ha ($399/acre)	$1112/ha ($450/acre)	$126/ha ($51/acre)
Switchgrass	13,450 kg/ha (6.0 tons/acre)	$956/ha ($387/acre)	$1080/ha ($437/acre)	$124/ha ($50/acre)
Pasture/hayland	5604 kg/ha (2.5 tons/acre)	$744/ha ($301/acre)	$1038/ha ($420/acre)	$294/ha ($119/acre)

variables held constant, as little as a 10% increase in crop yield can reduce crop production costs and increase net revenue enough to sway a farmer-producer to shift crop production from one crop to another. Thus, the economic portion of this analysis is heavily reliant on projected crop yields.

Average yields for corn and pasture/hayland at the county level have been obtained from POLYSYS,[14] a dynamic model of the US agricultural sector capable of estimating the competitive allocation of agricultural land and crop prices associated with changes in yield and management practices, as based upon National Agricultural Statistics Service and US Department of Agriculture (USDA) census data. National production requirements for POLYSYS include a baseline solution (typically from USDA) and policy or resource changes desired for a particular scenario. POLYSYS outputs include economic variables, such as county-level crop supply, national crop demands and prices, national livestock supply and demand, farm income, and land use, including forest harvest, afforestation, and pasture conversion.

Switchgrass yields used in BLOSM have been calculated from a continuous grid (56-meter resolution) of projected lowland (Alamo) switchgrass yields.[13] ArcGIS 9.3.1 software was used to produce zonal mean yield values for each of the 64 subbasins and to assign these values to agricultural and pastureland HRUs. The resulting yields range from 16.2 to 21.8 metric tonnes/ha-year (7.24 to 9.74 dry tons/acre-year) across the study area and are comparable to crop yields currently being measured at three-year-old switchgrass farms in East Tennessee (UTIA, pers. comm.).

Optimization modeling component

For the spatial-optimization-modeling portion of the analysis (BLOSM), we have integrated the hydrologic and economic outputs described earlier using a large spreadsheet model with an imbedded optimization solver (OpenSolver). The model selects switchgrass planting locations from the 5537 hectares (13 683 acres) of agricultural land and the 34 101 hectares (84 265 acres) of pasture/hayland represented by the 1054 eligible HRUs in the LLT watershed to produce a target tonnage of switchgrass. Land (in the form of HRUs) is selected for conversion while maximizing profit, minimizing nutrient and sediment concentrations at the outlets of the subbasins, or achieving a combination of these sustainability goals to the extent possible (per the six scenarios described in Table 1).

The 64 subbasins of the LLT watershed are linked in a graphical tree structure based upon a simplified stream flow network (Fig. 3(a)). Except for Subbasin 1 (the mouth of the LLT watershed), each subbasin has a unique subbasin immediately downstream, and multiple subbasins can flow into a given subbasin. As shown by the highlighted subbasins in Fig. 3(a), water flows from the forested upper reaches (e.g. Subbasin 45) down through more agricultural reaches (e.g. Subbasin 11) of the Little Tennessee River to the LLT watershed outlet at Subbasin 1. BLOSM estimates the water-quality impacts of land-use conversion in a particular subbasin through each of the downstream subbasins based upon the upstream/downstream subbasin-pair runs described earlier.

The decision variables for BLOSM are the proportion of each HRU dedicated to switchgrass – a value between 0 and 1 – as represented by x_i (Figs 3(b) and 3(c)). Because of the nature of the optimization problem, the HRUs tend to be either entirely dedicated to switchgrass or left in the base-case land use. However, when partial conversion occurs, we assume that the water-quality impact of converting a portion of an HRU to switchgrass is directly proportional to the SWAT-modeled impact of 100% conversion of that same HRU to switchgrass.

BLOSM calculates the expected change in profit as a component of the overall optimization objective (Fig. 3(b)). For this analysis, the change in revenue was calculated by assuming that the HRU was previously planted in either corn or pasture with net revenue defined by the values in Table 2. Thus, each HRU converted to switchgrass produced a profit.

BLOSM uses a target tonnage of switchgrass to be produced in the watershed as the key constraint of each spatial optimization scenario (set at 58 969 metric tonnes (65 000 tons/year) for this analysis). BLOSM allows for the incorporation of an additional constraint to limit the disproportionate conversion of a particular land-use type to switchgrass (e.g. the Limit Agricultural Land Conversion scenario).

For this analysis, we have used BLOSM to optimize water-quality improvement according to the optimization formulation shown in Figs 3(b) and 3(c). However, to ensure that basing the objective function on the average of the water-quality metric across the watershed did not lead to solutions that caused minimal improvements (or even decreases) in water quality in one subbasin in exchange for substantial improvement in another subbasin, we also developed an alternative optimization formulation. The alternative formulation considered the individual subbasins more explicitly by establishing a goal concentration for each water-quality metric in each subbasin and then penalizing the system for exceeding the goal. Because there is not yet definitive State guidance for stream nutrient concentrations in Tennessee, we used water-quality threshold values that were based on potential thresholds of stream eutrophication:[19] 1.0 mg/l for total nitrogen concentrations, 0.1 mg/l for total phosphorus concentrations, and 50 mg/l for total suspended sediment concentrations. We then defined target concentrations for each pollutant concentration at the outlet of each subbasin by comparing these threshold values to the SWAT-generated baseline values and best-achievable values. We assumed that: (i) the planting of switchgrass should not worsen the metric in the subbasin; (ii) the threshold value should be attained if possible; and, (iii) if the threshold were not attainable, then the value should be the best achievable. Because the target values could not be simultaneously obtained for all metrics in all subbasins, we introduced a set of slack variables and a set of weights that allowed BLOSM to violate a goal level at a 'price' determined by user-defined weights. Initial experimentation with this alternative formulation led to a solution very similar to that of the original formulation, and so those results are not presented at this time. But the comparison of the formulations is clearly an opportunity for further experimentation with BLOSM.

Weighting scheme

BLOSM uses a weighting scheme that takes into account the different scales of the sustainability metrics as well as the relative importance of each for the given analysis. For the Minimize Nitrogen scenario, we weighted the average nitrogen concentration by –1 and the other three metrics (phosphorus and sediment concentration and total profit) by zero. The weights for the other single-objective scenarios were produced in a similar manner and are shown in Table 3. We then developed a Balanced Objectives scenario to see what sort of outcome would be achieved when all three water-quality goals and economic profit were equally weighted. For the Balanced Objectives scenario, we used dimensionless weights calculated from each metric's maximum value, as derived from the results of the four single-objective scenarios. Thus, profit was weighted 0.00009216, the result of dividing 100 by 1 085 022 (the metric maximum for profit). Sediment was weighted by –3.4169, the result of dividing 100 by –29.267 (the largest sediment concentration reduction realized). These weights compensated for the different scales and units of the

Table 3. Changes in profit and water quality projected by the Biomass Location for Optimal Sustainability Model (BLOSM), as applied to the Lower Little Tennessee watershed under six land-use-conversion scenarios for switchgrass production. The shaded cells contain the weights used in the BLOSM optimization formulation.

Scenario	Change in total profit	Change in total nitrogen concentration	Change in total phosphorus concentration	Change in total suspended sediment concentration
Minimize Nitrogen	0	–1	0	0
	$941 588	–0.09 mg/l	–0.02 mg/l	–21 mg/l
Minimize Phosphorus	0	0	–1	0
	$882 239	–0.08 mg/l	–0.02 mg/l	–21 mg/l
Minimize Sediment	0	0	0	–1
	$798 360	–0.04 mg/l	–0.01 mg/l	–29 mg/l
Maximize Profit	1	0	0	0
	$1 085 022	–0.03 mg/l	–0.01 mg/l	–8 mg/l
Balanced Objectives	0.00009216	–1150.5	–5189.1	–3.4169
	$981 384	–0.08 mg/l	–0.02 mg/l	–25 mg/l
Limit Agricultural Land Conversion	0.00009216	–1150.5	–5189.1	–3.4169
	$902 529	–0.06 mg/l	–0.02 mg/l	–19 mg/l

metrics, normalizing all of the measurements into a 100-point scale. However, the Balanced Objectives solution changed such a large proportion of agricultural land (as compared to pasture/hayland) to switchgrass that we ran the Limit Agricultural Land Conversion scenario. This scenario used the same weighting scheme as the Balanced Objectives scenario (Table 3), but added a constraint to limit the conversion of agricultural HRUs to no more than 25% of the available agricultural land.

Results

BLOSM solutions resulting from the six scenarios summarized in Table 1 are compared in a histogram that displays the percentage of the maximum achievable target for each of the four sustainability objectives under each scenario (Fig. 4). The 'actual' changes in water quality and profit projected under each scenario are summarized in Table 3, and maps of projected changes in subbasin-level nutrient and sediment concentrations are provided as Fig. 5. The quantity and percent of land-use change projected under each scenario are summarized in Table 4, and maps depicting land-use configurations resulting from four of the scenarios are provided as Fig. 6. Our interactive website (http://blosm.ornl.gov) provides tools to visualize BLOSM results with additional histograms and maps.

Analysis

When all four sustainability objectives were considered simultaneously under the Balanced Objectives scenario, the solution achieved 85% or more of each indicator's maximum achievable target (Fig. 4). This means that 85–95% of the possible water-quality improvements and 90% of the possible economic profits from planting the target amount of switchgrass were realized when these four objectives were given equal consideration. This finding stands in sharp contrast to the Maximize Profit scenario which resulted in less than 45% of the possible nutrient and sediment concentration reductions being achieved when only profit was considered critical to the placement of switchgrass crops. Even when agricultural land conversion was limited to 25% of the total land area designated for switchgrass production, between 65% and 82% of the potential water-quality improvements were realized simultaneously with 83% of the maximum potential profit. Thus, our initial results indicate that it may be possible to address a combination of sustainability objectives simultaneously in a way that realizes substantial benefits for each individual objective, including profitability.

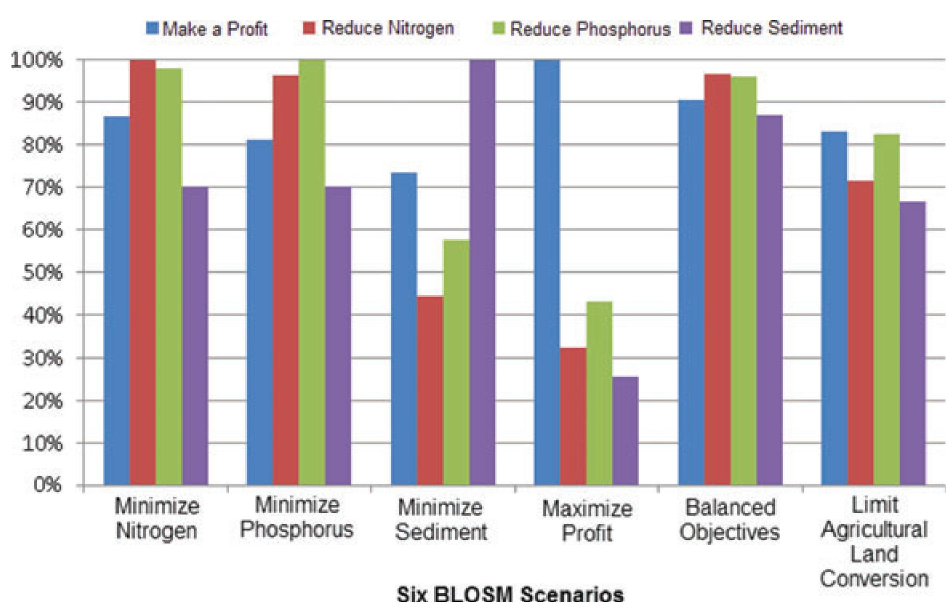

Figure 4. Biomass Location for Optimal Sustainability (BLOSM) projections of the percent of maximum achievable improvements for four sustainability metrics tested under six switchgrass planting scenarios. Each scenario sought to maximize a different sustainability goal, or combination of goals, for the Lower Little Tennessee watershed.

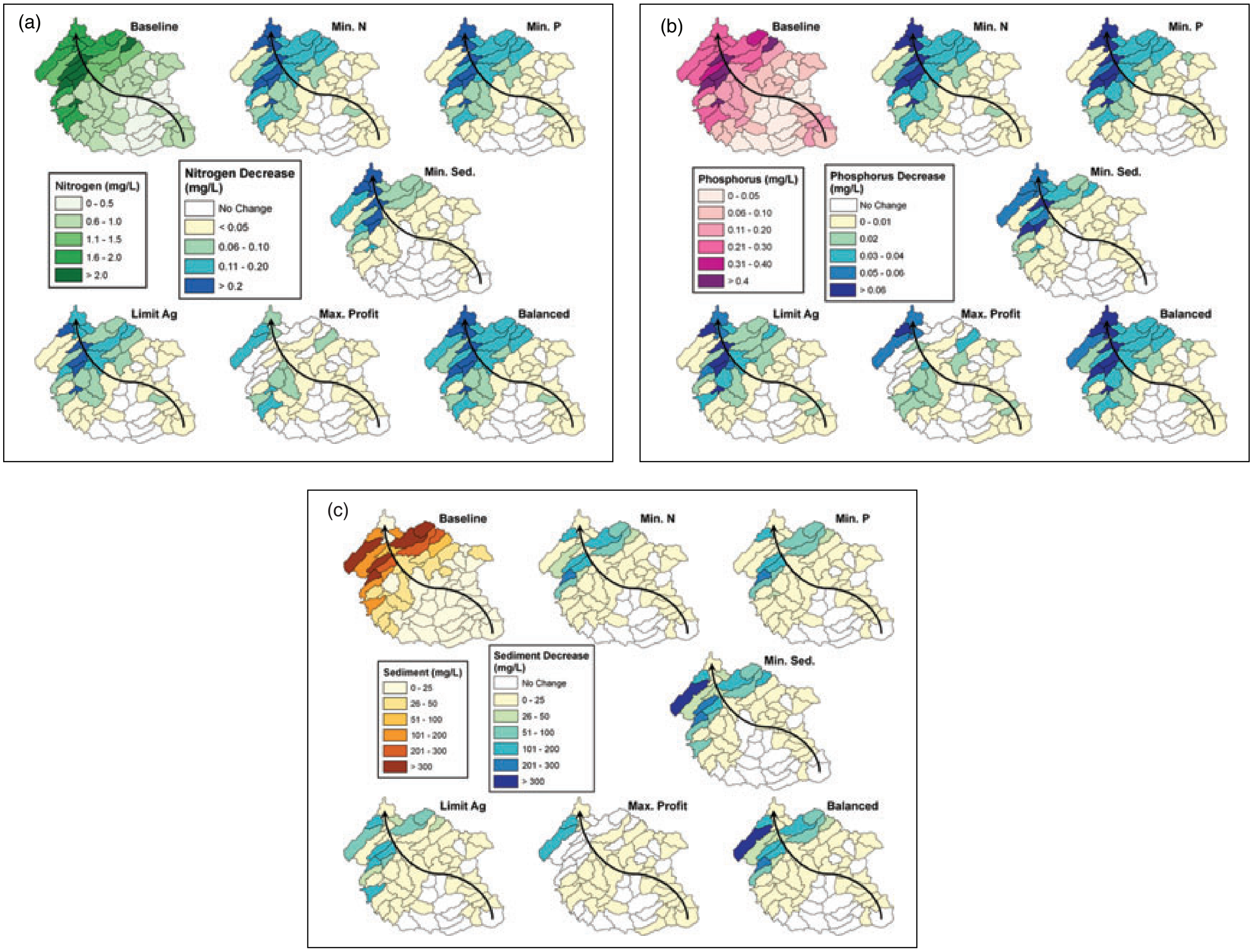

Figure 5. Maps of projected changes in subbasin-level water-quality metrics resulting from the six switchgrass planting scenarios run with the Biomass Location for Optimal Sustainability Model (BLOSM), as applied to the Lower Little Tennessee watershed: (a) changes in total nitrogen concentrations, (b) changes in total phosphorus concentrations, and (c) changes in total suspended sediment concentrations. Each of the six scenarios is compared to Baseline conditions of no land-use change. The black arrows indicate the general direction of water flow through the watershed from SE to NW.

All six scenarios resulted in some improvements to water quality when switchgrass was planted (Table 3, Fig. 5). However, the extent of the improvements to water quality varied by scenario, and sediment concentrations showed the greatest changes relative to baseline. The greatest water-quality improvements occurred in the downstream subbasins of the LLT watershed, where agricultural land is most highly concentrated.

Even though water quality improved under all scenarios, the projected mean watershed nutrient concentrations did not decrease substantially from baseline. Specifically, under the Minimize Nitrogen scenario, mean watershed concentrations of total nitrogen (TN) decreased by 0.08 mg/l. Under the Minimize Phosphorus scenario, mean watershed total phosphorus (TP) concentrations decreased by 0.02 mg/l. These changes in nutrient concentrations are within the natural temporal variability observed in agricultural streams.[28,29] Furthermore, the projected mean watershed nutrient concentrations under these two scenarios (TN = 0.94 mg/l and TP = 0.13 mg/l) are almost an order of magnitude higher than

Table 4. Projected land-use change resulting from six land-use-conversion scenarios run with the Biomass Location for Optimal Sustainability Model (BLOSM) for the Lower Little Tennessee Watershed. The results of each switchgrass planting scenario are compared to Baseline land-cover quantities of 5537 hectares (13 683 acres) of agricultural land (row crops) and 34 101 hectares (84 265 acres) of pasture/hayland calculated from the 2001 National Land Cover Dataset.

BLOSM Scenario	Balanced		Limit Agricultural Land Conversion		Maximize Profit	
Hectares (acres) of switchgrass	3451 (8527)		3250 (8032)		3117 (7702)	
	ha (acres) converted	Change from Baseline	ha (acres) converted	Change from Baseline	ha (acres) converted	Change from Baseline
Agricultural land	3344 (8262)	60.4%	1384 (3421)	25.0%	1477 (3649)	26.7%
Pasture/hayland	107 (265)	0.3%	1866 (4611)	5.5%	1640 (4053)	4.8%
BLOSM Scenario	Minimize Sediment		Minimize Nitrogen		Minimize Phosphorus	
Hectares (acres) of switchgrass	3476 (8589)		3467 (8566)		3459 (8547)	
	ha (acres) converted	Change from Baseline	ha (acres) converted	Change from Baseline	ha (acres) converted	Change from Baseline
Agricultural land	2443 (6036)	44.1%	3225 (7970)	58.2%	2813 (6951)	50.8%
Pasture/hayland	1033 (2553)	3.0%	241 (596)	0.7%	646 (1596)	1.9%

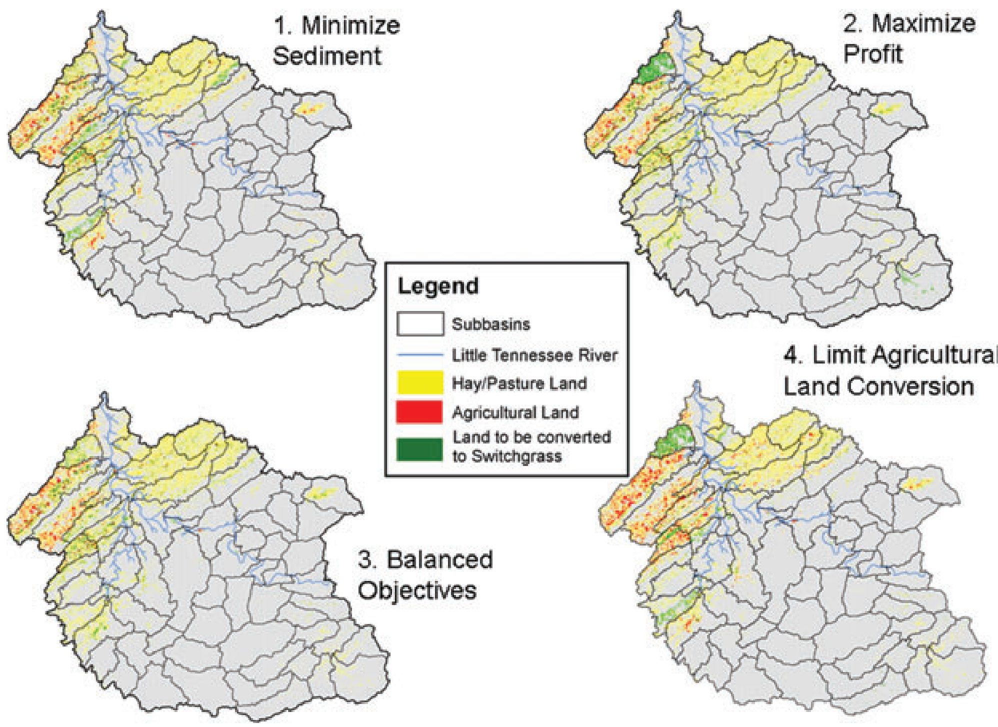

Figure 6. Projected agricultural land-use configurations for the Lower Little Tennessee watershed under four switchgrass planting scenarios run with the Biomass Location for Optimal Sustainability Model (BLOSM) as applied to the Lower Little Tennessee watershed: (a) minimizing sediment concentrations; (b) maximizing overall economic profit; (c) maximizing three water-quality objectives and economic profit to the extent possible using a 'balanced' weighting approach; and (d) using the 'balanced' approach with the additional constraint of limiting agricultural land conversion to 25% of the total land area converted. Each of these four scenarios would lead to the target production of 58 967 metric tonnes (65 000 tons) of switchgrass. The proportion of watershed area converted would range from 1.2% to 1.8%.

nutrient concentrations in reference (minimally impacted) streams in the area (reference TN = 0.148 mg/l and reference TP = 0.02 mg/l[15]). The elevated nutrient concentrations likely reflect the agricultural land use in the LLT watershed. Overall, results from the BLOSM model suggest that, in this area, planting switchgrass with the goal of minimizing water quality impacts decreases stream water nutrient concentrations while maintaining constant (or slightly increased) stream flows (although not discussed in this paper, water quantity was also tracked during each BLOSM run). However, the extent to which these decreases may be beneficial to stream and downstream ecosystems in the LLT watershed remains to be investigated and will require field-level observational data.

While the projected decreases in nutrient concentrations were minimal under all scenarios, the decreases in sediment concentrations with conversion to switchgrass were more substantial. For example, sediment concentrations in some subbasins near the mouth of the LLT watershed where switchgrass was planted decreased by 100–300 mg/l. While the largest decrease in sediment concentrations occurred under the Minimize Sediment scenario, the Balanced Objectives scenario resulted in a very similar outcome (Fig. 5(c)). By contrast, the smallest change in subbasin sediments (a decrease of 7 mg/l) occurred under the Maximize Profit scenario. In fact, under the Maximize Profit scenario, most subbasins experienced little (< 25 mg/l) to no change in total suspended sediment concentrations.

Watershed-wide profits increased under each scenario and by as much as $1 085 022 under the Maximize Profit scenario (Table 3). But, in addition to meeting less than half of all potentially achievable water-quality improvements, the Maximize Profit scenario concentrated land-use conversion largely within one subbasin (Fig. 6). The Balanced Objectives scenario achieved 90% of the profit goal while simultaneously achieving at least 85% of each water-quality goal (Fig. 4) and distributing land-use change rather evenly across the watershed (Fig. 6). However, the Balanced Objectives scenario and Maximize Profit scenario each led to conversion of 60% of existing cropland to switchgrass (Table 4), which may be unrealistic. With its additional constraint of converting no more than 25% of agricultural land to switchgrass, the Limit Agricultural Land Conversion scenario led to a solution that met about 83% of the profit goal while still achieving at least 65% of the water-quality goals (Fig. 4). The largest proportion of pasture/hayland (5.5%) was converted to switchgrass under this scenario (Table 4), and land-use change was concentrated within the same subbasin (subbasin 4) as the Maximize Profit scenario solution.

Discussion

BLOSM is a research tool – an optimization model that provides a benchmark of the best solution under certain assumptions. Results from BLOSM should not be seen as a prescriptive solution, since all of the land-use decisions associated with an HRU are not under the control of a single decision-maker. Assuming that the SWAT results are realistic, the BLOSM solutions indicate the limits to attaining certain goals as well as the potential for balancing the sustainability metrics. The optimization framework provides the ability to ask ‘What does water quality improvement cost in terms of lost profit?’ and similar questions.

The results obtained from this study demonstrate that there may be watershed-scale benefits realized by growing switchgrass in place of traditional crops. While many analyses focus on the negative environmental impact of grain-based energy crops[30] or effects of energy crops on factors other than water quality,[31] this study shows how the watershed-scale improvements in both water quality and farm profit can be achieved via selection of location for planting perennial energy crops. This analysis also shows that landscape designs can be developed for energy production in the context of other uses of the land.[32, 33]

During this analysis, the projected conversion of agricultural land (i.e. traditional row crops) and pasture/hayland to switchgrass improved water quality under each BLOSM scenario as measured by reductions in nutrient and sediment concentrations in streams. Watershed-wide profits were also realized under each scenario. Since only a small proportion of the LLT watershed (1.2–1.8% of the total area) experienced land-use change in meeting the switchgrass-production target of 58 967 metric tonnes (65 000 tons/year) under our six scenarios, it is possible that more-significant differences in water quality and profit would be observed if BLOSM were re-run with a higher feedstock production target.

Although the BLOSM model still needs to be calibrated with local field data to definitively project the amount of water-quality improvement that might actually be realized in the LLT watershed from planting switchgrass, the results obtained thus far indicate that planting switchgrass likely improves water quality in this area. This benefit probably accrues from the perennial growth of deep-rooted switchgrass that stabilizes soil and prevents erosion and sedimentation.[34–38] Furthermore, the conversion of cropland to switchgrass likely has beneficial effects on water quality in this study area because switchgrass is native to Tennessee and therefore requires very little fertilizer relative to traditional row crops such as corn and soybeans.

Results from this analysis also suggest that multimetric optimization achieves better results than those obtained by optimizing for a single factor. When both water-quality and profit targets were considered, the Balanced Objectives scenario solution nearly achieved the maximum achievable goals in the LLT watershed for increasing profit and reducing nutrient and sediment concentrations. While focusing on individual targets can better achieve those individual goals, this study illustrates that a combination of goals can be addressed simultaneously.

Achieving multiple environmental and socio-economic objectives for bioenergy sustainability will require some trade-offs between different goals, including profitability.[2] However, the results of this analysis indicate that substantial benefits for each individual objective may be obtained through a landscape design of dedicated bioenergy crop plantings. The acceptability of trade-offs to farmer-producers still needs to be explored. For instance, might they be willing to accept a small loss of profit in return for an improvement in water quality? Ultimately, it might be possible to include valuation of levels of environmental quality in a farmer-producer's production function. In this way, internalizing the external costs of the environment would be integrated into the modeling and multimetric approach to inform good policy. Sustainability parameters would then be embedded within the price of biomass and would ensure sustainable development by appropriately accounting for the ecological-services benefits realized from this production.

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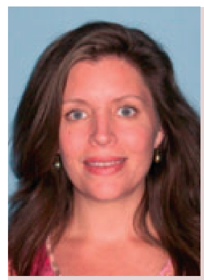
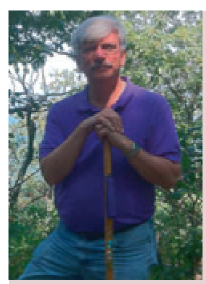


Esther Parish

Esther Parish is a research scientist at Oak Ridge National Laboratory. Her interests include bioenergy sustainability; land-use change; and impacts, adaptation, and vulnerability associated with climate change. She holds a BSc in Geology and Geophysics from Yale University and an MSc in Geography from the University of Tennessee.



Michael Hilliard

Michael Hilliard is a research scientist at Oak Ridge National Laboratory. His research interests include developing analysis tools for decision-makers that leverage optimization techniques and emerging computational technologies. Recent work includes applications to the various stages of the biofuel supply chain. He holds a PhD in Operations Research from Cornell University with an emphasis in optimization.

Latha Baskaran

Latha Baskaran is a research scientist at Oak Ridge National Laboratory. Her interests include bioenergy, water-quality modeling, habitat modeling, and land-use/land-cover change. She has also worked extensively with the SWAT hydrological model. She holds a Bachelor of Engineering in Geo-informatics from Anna University in India and an MSc in Geography from Pennsylvania State University.

Virginia Dale

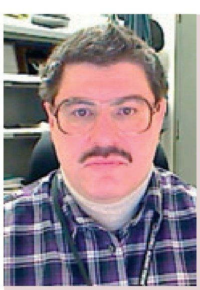
Virginia Dale is a Corporate Fellow in the Environmental Sciences Division at Oak Ridge National Laboratory (ORNL) and the Director of ORNL's Center for Bioenergy Sustainability. Her primary research interests are environmental decision-making, forest succession, land-use change, landscape ecology, ecological modeling, and sustainability of bioenergy systems. She obtained her PhD in Mathematical Ecology from the University of Washington.

Natalie Griffiths

Natalie Griffiths is a postdoctoral research associate in the Environmental Sciences Division at Oak Ridge National Laboratory. She studies anthropogenic influences on biogeochemistry and hydrology of aquatic and terrestrial ecosystems. She holds a BSc in Zoology and Physiology from the University of Toronto and a PhD in Biological Sciences from the University of Notre Dame.

Patrick Mulholland

Patrick Mulholland has recently retired after a distinguished career at Oak Ridge National Laboratory. His research interests include the ecology of streams, biogeochemistry and land/water interactions in forested catchments, watershed hydrology, wetland ecology, and climate-change effects on freshwater ecosystems. He has a PhD in Environmental Biology from the University of North Carolina at Chapel Hill and BSc and MSc degrees in Environmental Engineering from Cornell University.

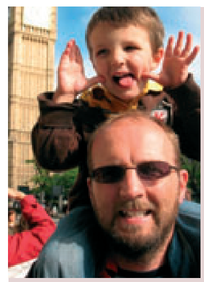


Alexander Sorokine

Alexandre Sorokine is a researcher at Oak Ridge National Laboratory. His major research interests and experience are in the fields of geospatial ontology, geographic databases and data models, parallel processing of geographic data, and environmental modeling. He received his Bachelor and Master's degrees in Physical Geography from Moscow State University and his PhD in Geography from the State University of New York at Buffalo.

Mark Downing

Mark Downing is a senior scientist at Oak Ridge National Laboratory. His research interests include technical and commercial development of biomass energy, as well as development of technologies for converting lignocellulosic feedstocks into fuels, power, and chemicals. He is Adjunct Professor of Agricultural Economics at the University of Tennessee, Knoxville, and obtained a PhD from Texas A&M University.



Richard Middleton

Richard Middleton is a scientist at Los Alamos National Laboratory. He specializes in energy infrastructure models, including developing models for CO_2 capture and storage, biofuels, and wind-farm development. He holds an MSc in GIScience from the United Kingdom's Leicester University and a PhD in Operations Research and Geography from the University of California at Santa Barbara.

Neil Thomas

Neil Thomas is a researcher at Oak Ridge National Laboratory with more than 20 years of experience in software analysis, design, and development for the US Department of Defense, Department of Energy, Department of Homeland Security, and Transportation Security Agency. He has a PhD in Industrial/Organizational Psychology and a Master's in Computer Science.