

An Integrated Modeling and Data Management Strategy for Cellulosic Biomass Production Decisions

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An Integrated Modeling and Data Management Strategy for Cellulosic Biomass Production Decisions

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Abstract: Emerging cellulosic bioenergy markets can provide land managers with additional options for crop production decisions. For example, integrating dedicated bioenergy crops such as perennial grasses and short rotation woody species within the agricultural landscape can have positive impacts on several environmental processes including increased soil organic matter in degraded soils, reduced sediment and nutrient loading in watersheds, and lower green house gas fluxes. Implementing this type of diverse bioenergy production system to maximize the potential environmental benefits requires a detailed understanding of the many interwoven aspects of environmental landscapes. This paper presents a dynamic framework-based integrated modeling and data management strategy that can design sustainable bioenergy cropping systems within the existing row crop production landscape of the Midwestern U.S. Critical environmental processes—including soil erosion from wind and water, and soil organic matter changes—are quantified by this integrated model to determine sustainable removal rates of agricultural residues for bioenergy production at the sub-field scale. Seven land management options for a 59 ha Iowa field are examined using the integrated model. These include a baseline case of sustainable residue removal and various incorporations of rye cover cropping and switchgrass use in marginal land. Relative to the baseline metrics, the adoption of rye cover crops with sustainable residue removal increases the total biomass sustainably available for biofuel production by 289% and reduces soil loss by 42%. Combining rye cover crops while displacing less productive and at-risk areas of the field with switchgrass increases the sustainable biomass available by 436% and decreases soil loss by 64%.

Keywords: integrated model; environmental landscape; soil erosion; sub-field analysis; cover cropping

1 INTRODUCTION

In 2007 the United States Federal Government passed the Energy Independence and Security Act (EISA) establishing a goal to produce 136 billion liters of biofuels by 2022 [EISA, 2007]. Accordingly, the agricultural-based ethanol biofuels industry grew from 1% of the U.S. fuel supply in 2000 to 7% in 2008 showing significant progress toward the EISA target. However, the Renewable Fuel Standard in the EISA has effectively placed a 57 billion liter cap on ethanol production from cornstarch as part of the 136 billion liter target for 2022. The remainder of the target is to be met with advanced biofuels, including cellulosic ethanol, biobutanol, biomass-based diesel, and other biofuels that are a direct replacement for

petroleum-based fuels. To reach and exceed the biofuels targets, strategies are needed to maximize the total productive capacity of the agricultural land resources.

The largest potential near-term source of cellulosic biomass to meet the EISA target is agricultural residues [U.S. DOE, 2011]. The key challenge of using agricultural residues for biofuel production is ensuring sustainable use of the resource. The definition of sustainable resource use is constrained to considering local environmental sustainability indicators for the scenarios investigated in this paper. The quantity of agricultural residues that can be removed sustainably is limited by a number of environmental factors including soil erosion and soil organic carbon [Wilhelm et al., 2010]. Recent studies have developed an integrated modeling strategy that considers multiple environmental factors in determining the quantity of agricultural residue that can be removed sustainably for biofuels production [Muth and Bryden, 2012a; Muth et al., 2012b]. Using this integrated model Muth et al. [2012b] found that 150 million metric tons of agricultural residues could have been harvested sustainably in the conterminous U.S. in 2011. Assuming cellulosic biofuel conversion rates of 330 liters per metric ton of feedstock [Aden et al., 2002; Phillips et al., 2011], these residues could provide 49.5 billion liters of biofuels. Accounting for roughly a third of the total target, this falls short of the EISA requirements; however, there are agronomic strategies that can help increase total productive capacity of the land by increasing the amount of residues that can be removed sustainably, and also by introducing highly productive dedicated bioenergy crops into current agricultural systems.

The use of cover crops such as winter rye within existing row crop rotations has been shown to increase the amount of agricultural residues that can be sustainably removed [Jokela et al., 2009; Villamil et al., 2006]. Removing agricultural residues can result in the loss of soil organic carbon and nutrients as well as increased soil erosion due to loss of surface cover. An appropriate cover crop can mitigate these issues and increase the amount of residue that can be removed sustainably. In addition, cover crops may reduce the requirements for chemical application and other synthetic inputs. Cover crops are chosen based on site-specific growing conditions for a given region. For example, winter rye has many qualities conducive to the Midwestern U.S. where cooler temperatures are typically seen in October after harvest. Once planted, winter rye produces rapid ground cover with an extensive root system and can withstand extremely low temperatures during a harsh winter.

Dedicated energy crops capable of producing high yields per unit area can potentially play a key role in providing biofuel feedstock sources. Several potential high yielding dedicated bioenergy feedstocks are being developed including sweet sorghum, energycane, miscanthus, and switchgrass. These feedstocks are being targeted for use on marginal and less productive lands. However, incorporating these feedstocks into landscape positions that are contributing to environmental externalities (*i.e.* leaching, runoff or erosion) under current soil and crop management practices may provide an opportunity to minimize the negative environmental impacts of feedstock production while providing additional biomass for biofuel production.

Implementing these agronomic strategies requires understanding the agricultural systems at the field and sub-field scale. Sub-field scale variability in soil characteristics, surface slope, and grain yield has been shown to significantly impact sustainable residue removal potential [Muth et al., 2012c]. The same characteristics that impact residue removal potential at the sub-field level, can define those areas within fields that are at-risk and marginal for standard row crop production practices. At-risk and marginal areas are defined as areas on the landscape which are more susceptible to environmental degradation considering sustainability indicators associated with soil erosion and soil organic carbon.

This study uses the sub-field scale integrated modeling strategy developed by Muth et al. [2012c] to investigate two agronomic strategies, cover crops and integrating switchgrass into the existing row crop production system. The investigation of these agronomic strategies will consider three primary issues: total sustainable biomass available for biofuel production, soil loss from erosion, and soil organic carbon. A 59 ha field in north central Iowa is selected where high-fidelity data are readily available from various GIS resources and precision farming technology. Baseline performance is established using existing management practices and cropping rotations for the field. Six additional land management options are then considered using rye winter cover between growing seasons and switchgrass in selected areas.

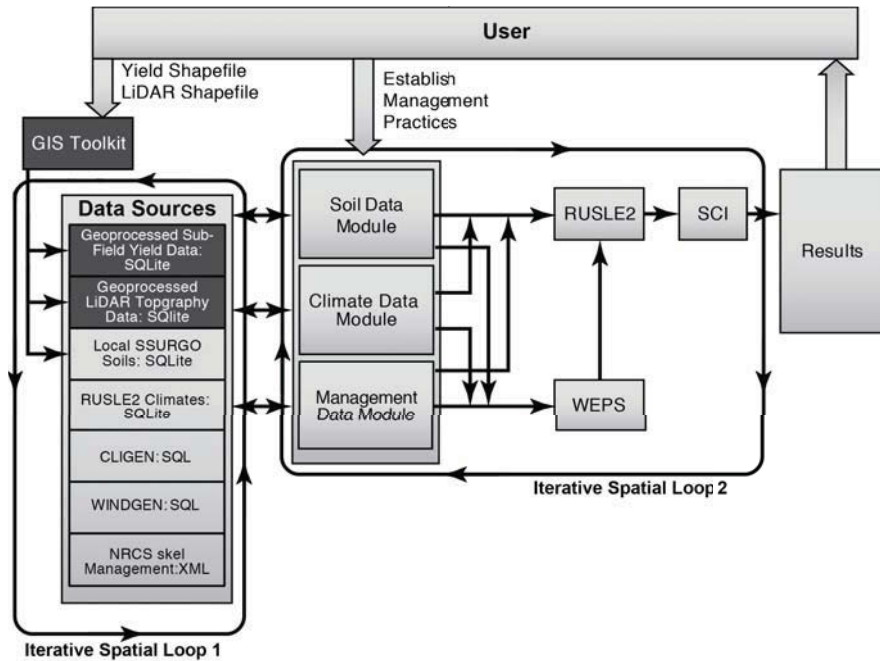


Figure 1. Sub-field integrated modeling framework used for this study [Muth et al., 2012c].

2 MODELS AND METHODOLOGY

The sub-field scale integrated model developed by Muth et al. [2012c] (Fig. 1) is used for this study. This integrated model couples the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) [USDA-NRCS, 2011a], Wind Erosion Prediction System (WEPS) [USDA-ARS and NRCS, 2008], and Soil Conditioning Index (SCI) [USDA-NRCS, 2012a] models with a multi-scale set of databases describing crop yield, surface topography, soil characteristics, climate, and land management data. The modeling framework used for the integrated model is VE-Suite [McCorkle and Bryden, 2007]. The sub-field model utilizes high fidelity input data sets providing soil characteristics, surface slope, and grain yield. Crop yield data are supplied from the combine harvester yield monitor systems. Each crop yield data point is a base spatial unit for the sub-field scale integrated model, and each of these points represents a spatial element at the 1 m scale. Surface topography data at the 1 m scale are supplied by light detection and ranging (LiDAR) through airborne laser scanning [Vitharana et al., 2008; McKinion et al., 2010] by the GeoTREE LiDAR mapping project [GeoTREE, 2011]. Soil characteristics data are provided by the Soil Survey Geographic (SSURGO) Database [USDA-NRCS, 2011b], an open access national soil survey database provided by NRCS. SSURGO data are at the 10–100 m scale. Climate data are at the county scale (approximately 10–100 km)

and are provided by three sources: NRCS managed RUSLE2 climates, CLIGEN, and WINDGEN. Land management data are provided by an NRCS-managed database, which is housed in the integrated model as an XML data structure. Management data are a field scale characteristic.



Figure 2. Aerial image of 59 ha field located in Cerro Gordo County, north central Iowa. The region of interest is marked by a light-orange outline.

3 CASE STUDY

This study uses the sub-field integrated model to investigate the impacts of two agronomic strategies, cover crops and switchgrass, on at-risk field locations within a 59 ha field located in Cerro Gordo County, north central Iowa (Fig. 2). This field is typical of Midwestern U.S. agricultural land used in row crop production systems. It has significant diversity in soil properties, surface slope, and crop yield. This field is in a corn-soybean rotation. Tillage management practices for this field are modeled as reduced tillage. Three treatments are investigated for this field.

- **Treatment 1 - Baseline assessment determining sustainable residue removal potential.** This treatment uses a standard corn-soybean rotation with reduced tillage assumptions [Muth et. al., 2012c]. Residue removal is modeled with NRCS rake and bale operations that collect 52% of the corn residue/stover. The ratio of grain to plant biomass is assumed to be 1:1. Sustainable removal

Table 1. The three management treatments used in this study with operation timings in month/day format.

Corn/Soybean		Corn/Soybean w/ Rye Cover		Perennial Switchgrass	
4/20 Year 1	Fertilizer Application	4/20 Year 1	Fertilizer Application	11/1 Year 1	Chisel Plow
5/1 Year 1	Field Cultivation	5/1 Year 1	Field Cultivation	4/15 Year 2	Field Cultivation
5/1 Year 1	Plant Corn	5/1 Year 1	Plant Corn	4/15 Year 2	Plant Switchgrass
10/15 Year 1	Harvest Corn	10/15 Year 1	Harvest Corn	12/15 Year 3	Harvest Switchgrass
10/15 Year 1	Rake Residue	10/15 Year 1	Rake Residue	12/15 Year 4	Harvest Switchgrass
10/18 Year 1	Bale Residue	10/18 Year 1	Bale Residue	12/15 Year 5	Harvest Switchgrass
11/1 Year 1	Chisel Plow	10/25 Year 1	Chisel Plow	12/15 Year 6	Harvest Switchgrass
5/15 Year 2	Plant Soybeans	10/26 Year 1	Plant Rye Cover	12/15 Year 7	Harvest Switchgrass
10/10 Year 2	Harvest Soybeans	5/25 Year 2	Kill Rye	12/15 Year 8	Harvest Switchgrass
		6/1 Year 2	Plant Soybeans		
		10/10 Year 2	Harvest Soybeans		

requires that soil erosion is less than the tolerable soil loss (T value) [NRCS, 2012b] for each soil type established by NRCS and soil carbon is not decreasing.

- Treatment 2 - Sustainable residue removal with a rye cover crop. In this treatment the winter rye is introduced following corn harvest to provide soil protection and improvement over the winter months. As shown in Table 1, the winter rye is planted with a drill following the corn grain and residue harvest and tillage in the fall. The winter rye is killed in the spring with a herbicide application.
- Treatment 3 - Incorporating switchgrass production in selected areas of the field where a combination of factors is found. These factors are low grain yield and continuous areas of unsustainable residue removal from the second treatment. These factors are chosen for two reasons. First, areas in the field where grain yield are low are more likely to see an economic benefit for the land manager with the transition to an alternative crop. Second, continuous areas where residue removal is unsustainable with the cover crop treatment will represent at-risk and marginal areas of the field. The switchgrass production system was assumed to have a two-year establishment period and six years of stand productivity before reestablishment was required.

The results from these three treatments are used to examine the total biomass sustainably removed, the area of the field managed sustainably, and annual average soil loss comparing seven different scenarios shown in Table 2. The first scenario is the baseline Treatment 1. The second scenario is Treatment 2. The third scenario incorporates switchgrass as described in Treatment 3, but not including the winter rye cover on the remaining corn-soybean area of the field. The fourth scenario combines Treatments 2 and 3 by incorporating the switchgrass and including the rye cover on the remaining field area. Scenarios 5, 6, and 7 present results representing only the areas of the field which are identified for switchgrass production. These areas are given focus because they are the most at-risk areas of the field and present the best opportunity for significant environmental benefits. Scenario 5 shows the characteristics of this area of the field under the baseline Treatment 1 management practices. Scenario 6 represents what happens in this area of the field with the cover crop, and Scenario 7 provides the impact on this area of the field with the introduction of switchgrass. Scenarios 5, 6, and 7 are included to emphasize the contributions from the identified marginal and at-risk areas of the field on soil loss and unsustainable management practices.

Table 2. Annual residue removal, fraction of field managed sustainably, and annual soil loss for seven different management plans.

Rake and Bale Removal	Reduced Tillage		
	Annual Sustainable Residue (metric tons)	Percentage of Field Managed Sustainably	Annual Soil Loss (metric tons)
Scenario 1 (Corn/Soy)	36	21%	316
Scenario 2 (Corn/Rye/Soy)	140	83%	182
Scenario 3 (Corn/Soy & Switch)	113	48%	155
Scenario 4 (Corn/Rye/Soy & Switch)	193	96%	114
Scenario 5 (Switch)	86	100%	11
Scenario 6 (Corn/Soy in Switch area)	10	18%	172
Scenario 7 (Corn/Rye/Soy in Switch area)	33	61%	79

4 RESULTS

A majority of the field (79%) is managed unsustainably using rake and bale removal at the sub-field scale (Fig. 3f). The results for this treatment are represented as Scenario 1 in Table 2. The limiting factor leading to unsustainable residue removal is soil carbon ($SCI < 0$). Wind and water erosion are shown to cause considerable soil loss in regions of elevated slope and sand fraction ($>3.5\%$ and $>55\%$, respectively). The steeper/longer the slope of the field, the more water erosion will come into play and sandy soils are typically very susceptible to wind erosion due to a lack of aggregate structure. This effect is compounded as high erosion rates and sandy soils produce adverse growing conditions for conventional row crops creating a cycle of poor vegetative cover, resulting in reduced residue returned to the soil, and creating continued erosion. This can be seen in Figure 3 as the low organic matter, the high sand fraction, the steep slopes, and the low yields all align in the south-west/west-central area of the field. As would be expected, the 21% of the field that is managed sustainably is in those soils where organic matter is high ($> 5.5\%$) and the sand fraction is low ($< 40\%$).

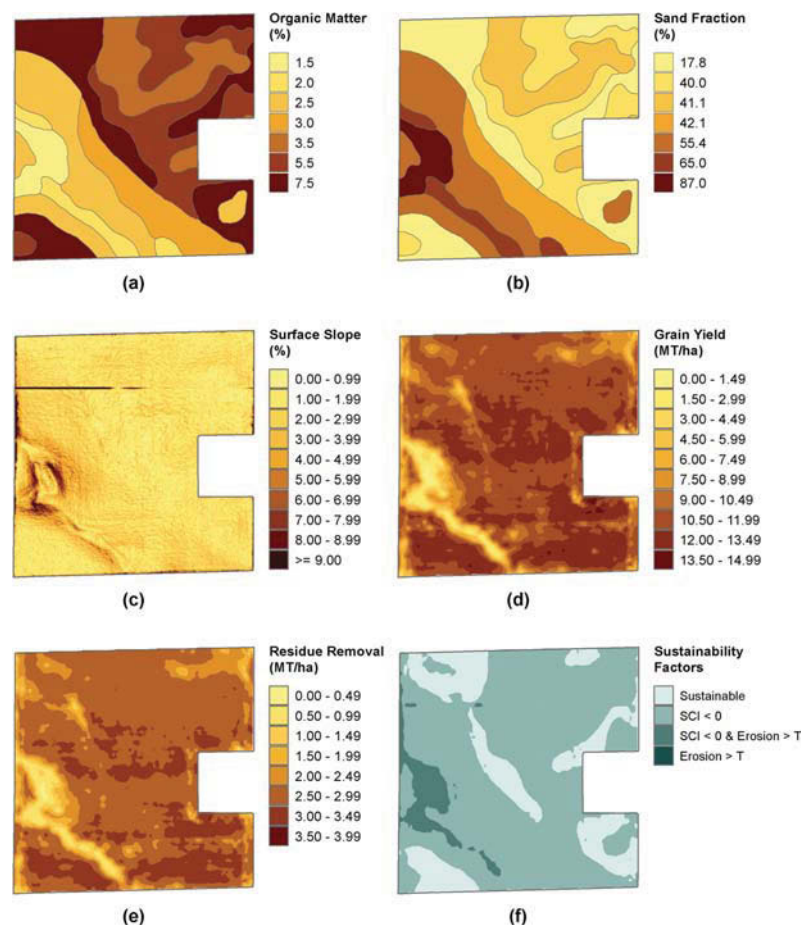


Figure 3. Residue removal and sustainability evaluation for NRCS rake and bale management practice.

Areas of the field targeted for potential switchgrass production are designated with a purple outline in Figure 4a. These regions could benefit from perennial switchgrass production, which would mitigate the existing limiting factors while producing 86 metric tons of biomass feedstock each year. As shown in Table 2, this would be an annual increase of 53 metric tons of biomass material over corn

stover collected in the rye cover scenario. As shown in Figure 4b, 100% of the switchgrass would be managed sustainably and when incorporated into the existing rye cover scenario, a total of 193 metric tons of residue per year could be sustainably removed from the field with only 4% of the hectareage unsustainable. It is important to note that 183 MT of corn grain and approximately 39 MT of soybeans (assuming a constant 2000 kg/ha yield) would be lost for food/fodder production in year one and year two respectively if supplanted by switchgrass.

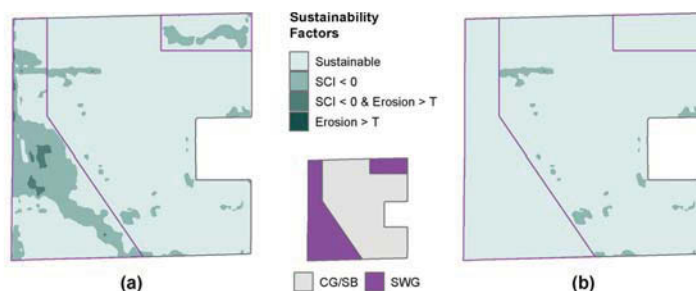


Figure 4. a) Sustainability analysis for rye cropping scenario; approximately 20 hectares of the field are identified for potential switchgrass production within the purple outline. b) All switchgrass hectareage is found to be sustainable.

5 CONCLUSIONS

A sub-field scale integrated model is applied to investigate the impact of two agronomic strategies on total sustainable biomass available for biofuel production, soil loss from erosion, and soil organic carbon within a typical field in Iowa. The integrated modeling framework combines data from multiple spatial scales to perform high fidelity sub-field scale analyses considering soil erosion from wind and water, and soil organic carbon. This multi-scale integrated modeling capability allows investigation of advanced agronomic strategies that can increase the total productivity of the land and increase long term sustainability of the agronomic system. This study uses the integrated model to investigate cover crop management practices, and integrating switchgrass on non-productive and at-risk areas in the field. The use of rye cover crops increases the total biomass sustainably available for biofuel production by 289% while reducing soil loss by 42%. Through the use of cover crops and displacing less productive and at-risk areas of the field with switchgrass the total biomass sustainably available for biofuel production is increased by 436% while decreasing soil loss by 64%. A loss of around 110 MT of grain per year would be realized from displacement of existing agricultural production; however, this output is seemingly unsustainable as shown and will lead to increasingly poor soil conditions. Future development and application of the integrated model will focus on considering additional environmental factors including greenhouse gas emissions and nutrient use efficiency. Future work will also investigate the economic impacts of the management decisions shown here to have significant environmental benefits.

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