LANDSCAPE MANAGEMENT FOR SUSTAINABLE SUPPLIES OF BIOENERGY FEEDSTOCK AND ENHANCED SOIL QUALITY

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Abstract

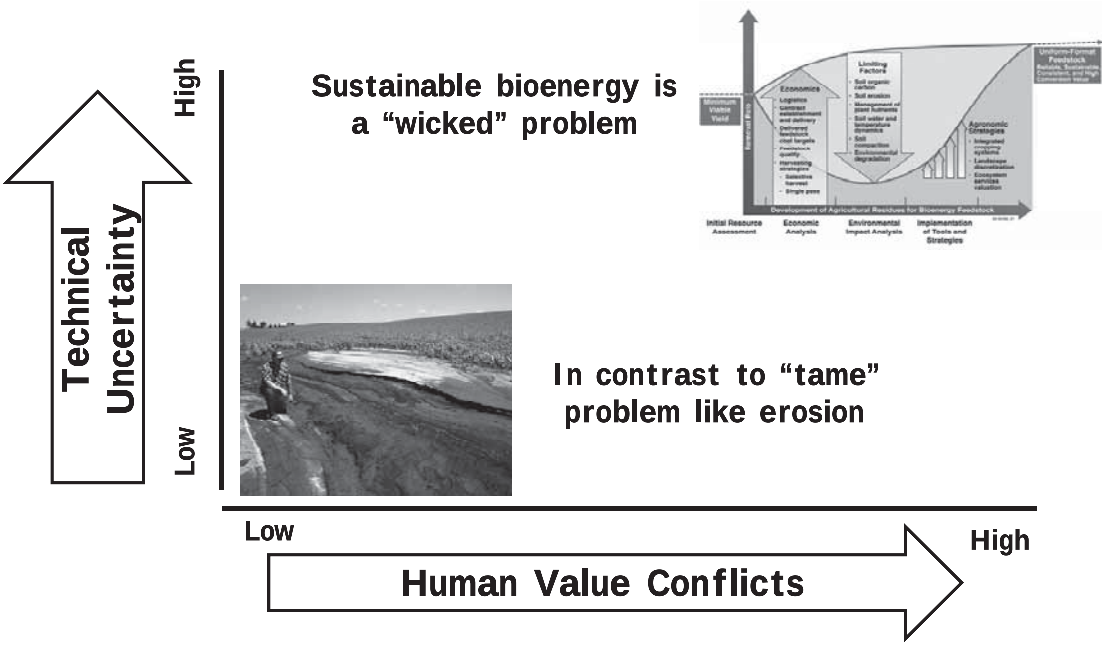
Agriculture can simultaneously address global food, feed, fiber, and energy challenges provided our soil, water, and air resources are not compromised in doing so. As we embark on the 19th Triennial Conference of the International Soil and Tillage Research Organization (ISTRO), I am pleased to proclaim that our members are well poised to lead these endeavors because of our comprehensive understanding of soil, water, agricultural and bio-systems engineering processes. The concept of landscape management, as an approach for integrating multiple bioenergy feedstock sources, including biomass residuals, into current crop production systems, is used as the focal point to show how these ever-increasing global challenges can be met in a sustainable manner. Starting with the 2005 Billion Ton Study (BTS) goals, research and technology transfer activities leading to the 2011 U.S. Department of Energy (DOE) Revised Billion Ton Study (BT2) and development of a residue management tool to guide sustainable crop residue harvest will be reviewed. Multi-location USDA-Agricultural Research Service (ARS) Renewable Energy Assessment Project (REAP) team research and on-going partnerships between public and private sector groups will be shared to show the development of landscape management strategies that can simultaneously address the multiple factors that must be balanced to meet the global challenges. Effective landscape management strategies recognize the importance of nature's diversity and strive to emulate those conditions to sustain multiple critical ecosystem services. To illustrate those services, the soil quality impact of harvesting crop residues are presented to show how careful, comprehensive monitoring of soil, water and air resources must be an integral part of sustainable bioenergy feedstock production systems. Preliminary analyses suggest that to sustain soil resources within the U.S. Corn Belt, corn (*Zea mays* L.) stover should not be harvested if average grain yields are less than 11 Mg ha^{-1} (175 bu ac^{-1}) unless more intensive landscape management practices are implemented. Furthermore, although non-irrigated corn grain yields east and west of the primary Corn Belt may not consistently achieve the 11 Mg ha^{-1} yield levels, corn can still be part of an overall landscape approach for sustainable feedstock production. Another option for producers with consistently high yields (> 12.6 Mg ha^{-1} or 200 bu ac^{-1}) that may enable them to sustainably harvest even more stover is to decrease their tillage intensity which will reduce fuel use, preserve rhizosphere carbon, and/or help maintain soil structure and soil quality benefits often attributed to no-till production systems. In conclusion, I challenge all ISTRO scientists to critically ask if your research is contributing to improved soil and crop management strategies that effectively address the complexity associated with sustainable food, feed, fiber and fuel production throughout the world.

Introduction

A recent report by the Chicago Council on Global Affairs concluded that "a landscape-based framework is needed to evaluate agricultural, energy, and environmental trade-offs inherent in bioenergy production systems (1). But, what is landscape management and why is it important for sustainable biofuel feedstock production and enhanced soil quality? Landscape management as defined herein is a land-use decision process that recognizes the importance and impact of nature's diversity and acknowledges both, immediate and long-term as well as on- and off-site impacts associated with every soil and crop management decision.

When focusing on complex agricultural production systems that are being challenged to meet global food, feed, fiber, and renewable fuel needs, why is diversity important? Simply stated, a diverse landscape provides multiple ecosystem services including: (1) feedstock for bioenergy, (2) enhanced nutrient cycling, (3) multiple pathways for sequestering carbon, (4) food, feed, and fiber resources, (5) filtering and buffering processes, (6) wildlife food and habitat, (7) soil protection and enhancement of soil quality, and (8) economic opportunities for humankind. If landscape management is so important, why is it a difficult concept for some to grasp and what barriers need to be overcome to implement it for sustainable bioenergy feedstock supplies and enhanced soil quality? This too is a very complex question, so perhaps illustrating it as a "wicked" problem (Figure 1) is an appropriate way to show why conservation programs of today are so much more challenging than during past decades (2). Wicked problems are those difficult-to-describe issues that are subject to considerable political debate. They tend to arise from civil society, not from experts, and they are often thrust upon policymakers and scientists. Wicked problems tend to have neither a clear definition nor an optimal solution, and attempts to solve them can easily cause the problem to change. Addressing wicked problems does not tend to lead to definitive "solutions." Instead, the action often results in outcomes that are simply "better or worse." In other words, wicked problems are not "solved" but rather they are "managed."

Unfortunately, ISTRO scientists no longer have the luxury of focusing solely on single issues such as the perils of wind, water or tillage erosion. Value-laden issues involving different human perceptions of sustainability and complex tradeoffs, presented in the press as "food versus fuel" (3) rather than optimistically as the potential for abundant food, feed, fiber and fuel with appropriate land management, are critical factors influencing research and education programs for all of us. More frequently than ever before, conservation goals become subordinate to policy goals including protection of income and wealth for a few at the environmental expense of many.



Adapted from S.S. Bete, 2010

Figure 1. An illustration of the complexity and "wickedness" of landscape management.

Landscape management for sustainable bioenergy feedstock production can be illustrated as strategies striving for balance (Figure 2) among economic drivers favoring the use of soil and water resources to produce feedstock materials and ecologically limiting factors that would minimize feedstock (*i.e.* crop residue) harvest to ensure that no ecosystem services including soil quality are compromised (4). With regard to sustainable biofuels crop production, landscape management also recognizes there are many different potential feedstock materials each with both advantages and disadvantages.

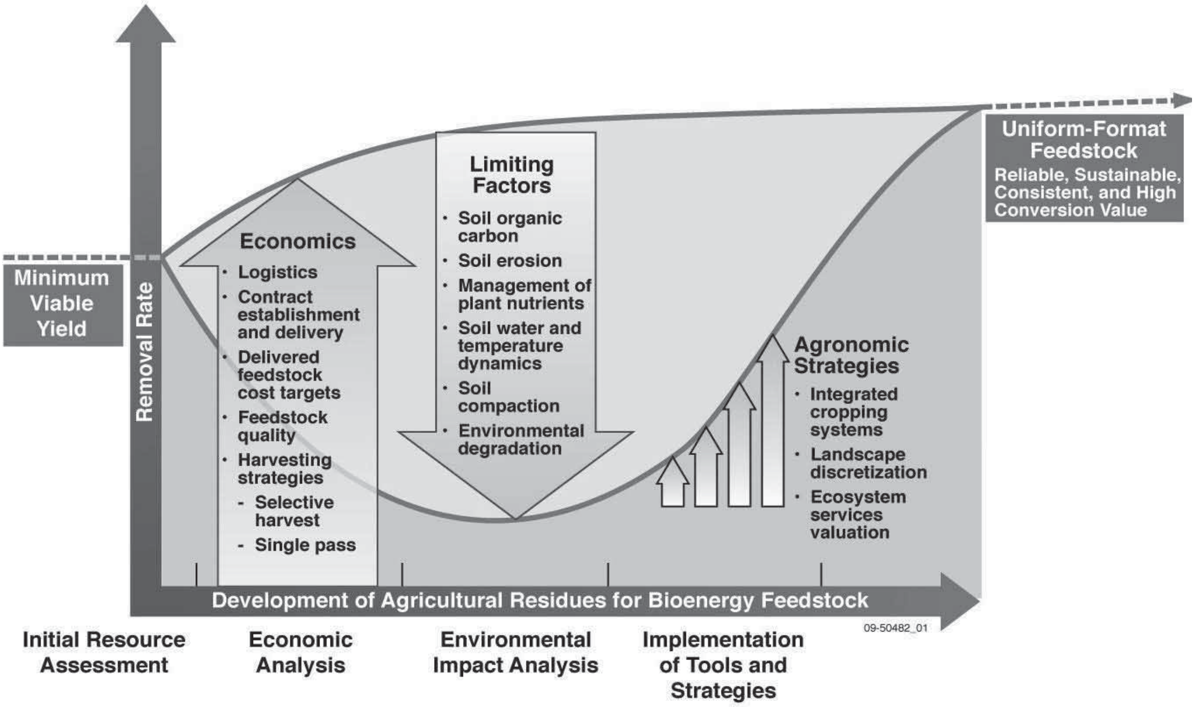


Figure 2. An illustration of competing economic drivers and environmental sustainability forces that must be balanced to achieve sustainable cellulosic feedstock supplies to support the transition from fossil to renewable fuels.

Potential bioenergy feedstock materials can be grouped into four broad categories: (1) agronomic crops such as corn, soybean (*Glycine max*), sweet sorghum (*Sorghum bicolor*) and sugarcane (*Saccharum spp.*), (2) dedicated perennial herbaceous crops such as switchgrass (*Panicum virgatum*) and *Miscanthus*, (3) woody species belonging to the genus *Salix* (willow) or *Populus* (cottonwood, poplar) in the Salicaceae family, eucalyptus (*Eucalyptus spp.),* sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), loblolly pine (*Pinus taeda* L), black locust (*Robinia pseudoacacia* L.), silver maple (*Acer saccharinum* L.), and shrub willow (5), and (4) residuals which include biomass materials that are left over from other processes – some of it currently used and useful, some of it considered waste material that must be managed carefully to prevent unintended ecological damage.

There are many challenges associated with adopting landscape management to ensure sustainable biofuel feedstock production, but this presentation will focus on just three including: (1) multiple interactions (e.g. air, water, soil, biota) – many that cannot be equivalently described or quantified; (2) balancing difficult-to-monitize factors (e.g. soil quality) with those that can more easily be monetized (e.g. yield); and (3) tradeoffs between long-term ecosystem protection and/or improvement and profit or return on investments which often are more short term.

Why is landscape management important in a world dominated by short-term economic concerns that focus primarily on easily monetized factors for decision making? From a societal perspective, a diverse landscape provides many more ecosystems services than simple systems focused on a limited number of crops. But what about financial costs or potential profit losses associated with implementing diverse landscape management strategies? Without a doubt, for current energy assessments fossil fuels have a significant competitive edge that is not likely to disappear soon (1). Currently, most bioenergy technologies tend to be smaller in scale and less efficient than fossil fuel counterparts. Furthermore, in addition to process efficiencies and economies of scale, fossil fuels currently have many other important advantages. Substantial existing energy infrastructure is already depreciated making its cost basis a fraction of that required for new technologies. Also, many energy markets are either monopolies or oliogopies which make market access very difficult for new entrants. Supportive policies and subsidies are therefore needed to encourage adoption of practices whose ecosystem service benefits are clear but currently unrecognized by markets. At the same time, markets for those ecological attributes must be created as soon as possible to ensure that appropriate long-term economic signals are in place for socially beneficial behavior (1). In other words, landscape management is difficult because it is a “wicked” problem rather than a “tame” one (*i.e*. soil erosion), and there is little uncertainty and virtually no human value conflicts involved when addressing it.

So how can producers implement landscape management? First they must assess all impacts of current land use decisions and management practices (Table 1). Then they must identify the most promising options for changing current landscape management practices (Table 2). Building on science-based, long-term field and laboratory research and using appropriately calibrated simulation models to predict optimum solutions, new management strategies can then developed and used to balance food, feed, fiber, and biofuel feedstock production for a variety of current and/or advanced biofuels.

Table 1. Assessment questions based on the NRCS Soil-Water-Air-Plant-Animal (SWAPA) model for evaluating current practices before designing a landscape management plan.

Resource	Critical Question
Soil	Is long-term soil quality improving or degrading?
Water	What are the surface and subsurface water quality impacts of current practices?
Air	What are the air quality (e.g. PM10, odors, GHG) impacts of current practices?
Plant	What cropping system is best for this landscape? Do I have the best spatial and temporal arrangement of plants?
Animal	Are livestock production systems affecting environmental quality?

Table 2. Potential landscape management practices that could facilitate conservation, provide bioenergy feedstock, and enhance soil quality.

Conservation Practice		
Riparian buffers	Re-saturated riparian buffers	Riparian forest buffers
Two-stage ditches	Nutrient interception wetlands	Riparian herbaceous buffer
Contour buffer strips	Vegetative barriers	Filter strips
Grassed waterways	Windbreaks	Field borders

The Residue Tool is a newly developed modeling framework for helping design landscape management strategies for sustainable feedstock production . Developed in partnership with a Department of Energy (DOE) Idaho National Laboratory (INL) engineer (6) the “tool” was developed using “field” data provided by several ARS REAP participants, Natural Resources Conservation Service (NRCS) soil survey data, and many other data sources. Through an advanced linkage of several simulation models, each optimized according to their individual guidelines, the “tool” uses the various data sources within a framework described by the limiting factor model (4) to assess sustainability based on multiple factors.

Usinsg NRCS SURGO soil database input for factors including soil organic matter and sand fraction, all agriculturally relevant soils were evaluated using a precursor to the current version of the "tool." County average crop residue and soil type slope estimates were then used for each relevant soil to estimate available crop residue for the Revised Billion Ton Report (BT2) report (7) report. Those estimates were much more spatially precise than values used for the initial 2005 Billion Ton Study estimates, but subsequent use with field-specific lidar elevation data and actual crop yields from farm combine operators have been used to obtain even better site-specific resolution and to create field-scale stover harvest maps for a several farms.

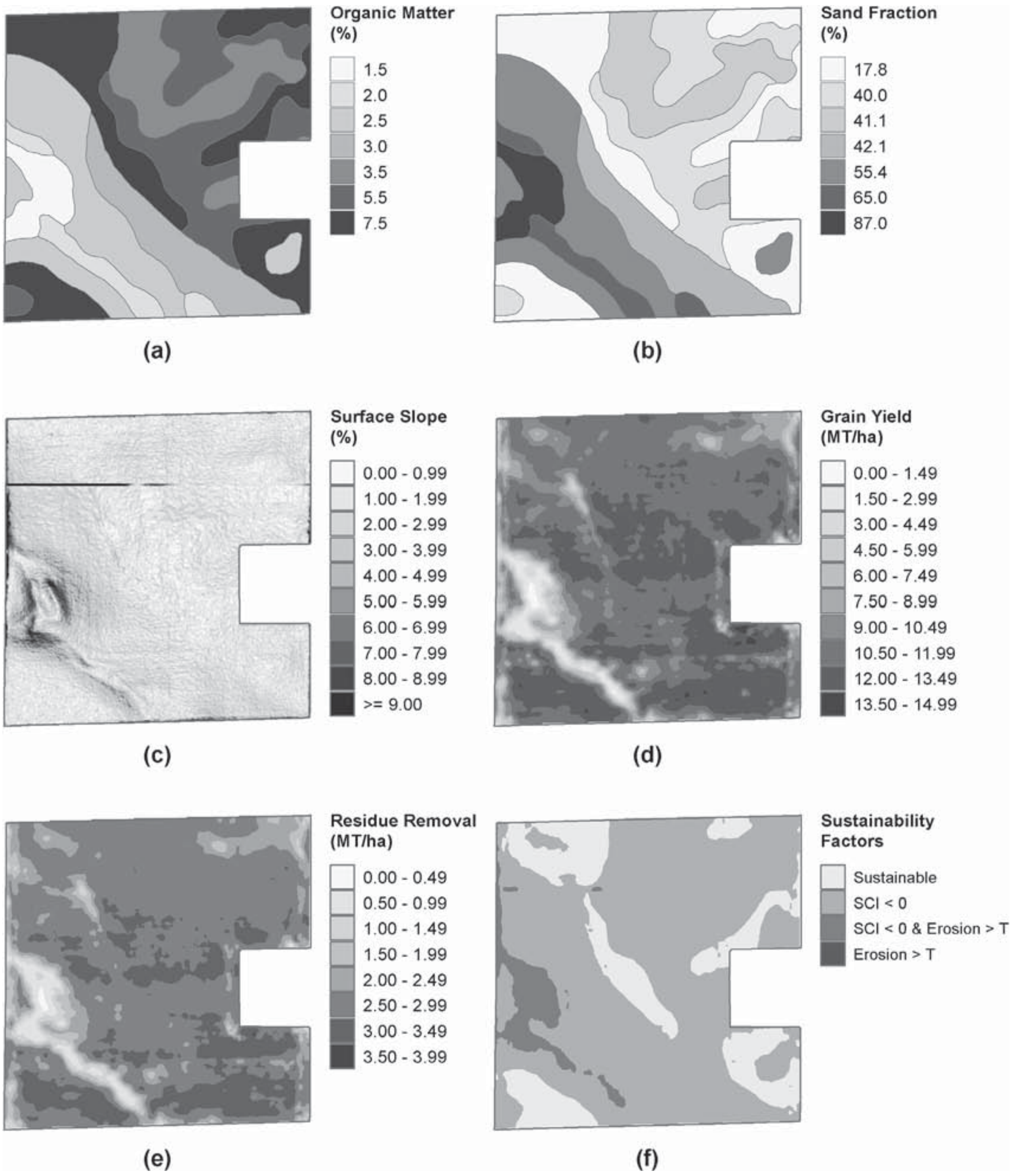


Figure 3. Soil properties (a and b), surface topography (c), grain yields (d), and residue removal tool results (e and f) for the 57 ha case study field in north central Iowa (from 6).

The “tool” can be used to identify areas in fields that are not suitable for harvesting crop residues because of one or more limiting factors (4). Then, by applying the concept of landscape management, those areas could used for other feedstock materials (e.g. switchgrass) that could have both a greater economic return and fewer environmental consequences, including further degradation of soil quality.

Residue tool case study

A case study using the residue “tool” was conducted to investigate the impacts of a conceptual implementation of landscape management principles. An integrated, sub-field version was used to investigate the effects of two landscape management strategies, cover crops and switchgrass, on at-risk field locations within a 57 ha field located in Cerro Gordo County, north central Iowa (Figure 3). This field is typical for Midwestern U.S. agricultural land used to produce row crops. It has significant diversity in soil properties, surface slope, and crop yield (Figures 3a-d) and is being managed in a corn-soybean rotation. Tillage management practices for this field are modeled as reduced tillage consistent with the definitions provided by the Conservation Technology Information Center (CTIC) (8). Figure 3e shows the model results projected for harvesting corn stover using a standard, commercially available rake and bale operations with the sub-field residue “tool”. Implementing the “tool” consistent with NRCS assumptions regarding water erosion, wind erosion, and soil organic carbon constraints, shows that the majority of the field would not be managed sustainably (Figure 3f). In fact, only 21% of the field can sustainably support rake and bale residue removal using these practices (6).

Diversity in slope, soil properties, and grain yield result in conditions that would make sustainable residue removal very challenging in this case study field, but those characteristics also make it an interesting field for exploring landscape management strategies using the sub-field version of the residue “tool”. Two strategies, (1) the use of cover crops and (2) identifying areas of the field where traditional row cropping may simply not be sustainable are therefore modeled to illustrate how more intensive landscape management could both increase biomass availability and protect soil quality. The “at-risk” areas within this case study field are designated using the purple outline in Figure 4a. Considering these strategies, two landscape management treatments were investigated in the following analysis.

<u>Treatment 1 - Sustainable reside removal with a rye cover crop</u>. 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 4, 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 an herbicide application.

Table 4. The three management scenarios used in this study with operation timings in month/day format.

Corn/Soybean		Corn/Soybean w/Rye		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 Soybean	5/25 Year 2	Kill Rye	12/15 Year 8	Harvest Switchgrass
		6/1 Year 2	Plant Soybean		
		10/10 Year 2	Harvest Soybean		

Treatment 2 - 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 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 landscape management scenarios shown in Table 2. The first scenario is the baseline row crop practices with rake and bale residue removal. The second scenario is Treatment 1, implementing a rye winter cover crop with baseline row crop practices. The third scenario incorporates switchgrass as described in Treatment 2, but not including the winter rye cover on the remaining corn-soybean area of the field. The fourth scenario combines Treatments 1 and 2 by incorporating the switchgrass and including the rye cover on the remaining field area. Scenarios five, six and seven 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, including soil quality improvement, when compared to the baseline row crop management practices. Scenario five shows the characteristics of the at-risk areas of the field for the baseline management practices. Scenario six represents what happens in the at-risk areas of the field with the cover crop, and scenario seven provides the impact on this area of the field with the introduction of switchgrass. Scenarios five, six, and seven are included to emphasize the contributions from the identified marginal and at-risk areas of the field on soil loss and unsustainable management practices.

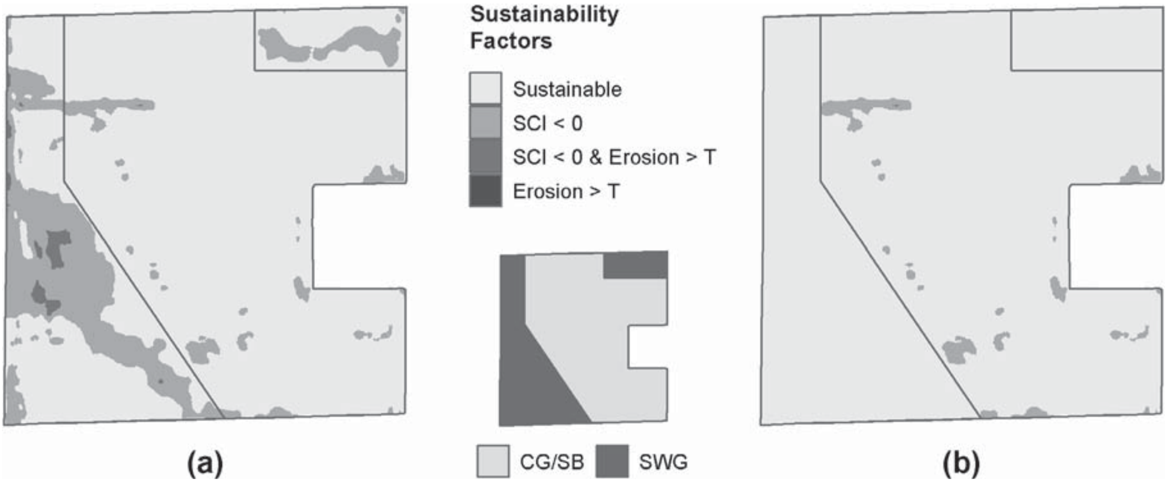


Figure 4.a) Sustainability analysis for rye cropping scenario; approximately 20 ha of the field are identified for potential switchgrass production within the purple outline. b) All switchgrass acreage is found to be sustainable.

Implementing switchgrass on the at-risk areas of the field identified in Figure 4 would mitigate negative ecological impacts from row crop production while producing 86 metric tons of biomass feedstock each year. As shown in Table 4, 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 area being classified as unsustainable.

With regard to bioenergy processing platforms, landscape management also means that multiple pathways are possible. Simply stated, the critical message is that diversity means there is no single solution! This includes using multiple feedstock materials, including various residuals or traditional waste streams (1, 9) processed using biochemical (fermentation), thermochemical (pyrolysis), and/or various direct catalyst reactions.

Table 5. 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

As illustrated by this case study, development of sustainable bioenergy feedstock production systems may also be an effective approach for restoring or improving soil quality. Again, the process begins by assessing and reevaluating new management practices (Table 2) using questions such as those outlined in Table 1. The Soil Management Assessment Framework (SMAF), which was previously used to evaluate long-term effects of harvesting crop residue for bioenergy production (10, 11, 12) can be used to monitor the soil quality effects. As previously shown after five years of continuous corn production near Ames, IA, U.S.A., soil bulk density (BD) increased slightly and therefore the SMAF BD score decreased (Karlen et al., 2011b). There was also a slight decrease in the total organic carbon (TOC) score, perhaps because stover harvest resulted in less annual carbon input into the soil, but measured TOC levels were not statistically different. Overall, the soil quality index (SQI) for that research site indicated the soil was functioning at 90 to 97% of its inherent potential after five years of stover harvest. In a near-by rotated corn and soybean study, TOC and soil-test K scores were much lower and the soil-test P score was slightly lower following the 2009 harvest. The net result, according to the SQI for the rotated site, was that the soil was functioning at 81 to 85% of its potential following three stover harvests. In both cases the SMAF assessments were consistent with those reported for other corn stover harvest sites (11).

Based on these studies and other, on-going collaborative REAP research, we are now suggesting that to sustain soil resources within the U.S. Corn Belt, corn stover should not be harvested if average grain yields are less than 11 Mg ha^{-1} (175 bu ac^{-1}) unless more intensive landscape management practices as illustrated by the previous case study are implemented. Furthermore for areas east and west of the primary Corn Belt where non-irrigated corn grain yields are frequently lower, corn can still be part of an overall landscape approach for sustainable feedstock production, but not the sole source of biomass. Finally, based on the soil quality assessments, the REAP team also suggests that producers with consistently high yields (> 12.6 Mg ha^{-1} or 200 bu ac^{-1}) may be able to sustainably harvest even more stover by decreasing their tillage intensity. This would also decrease fuel use, preserve rhizosphere carbon, and/or maintain soil structure, thus ensuring that soil quality benefits often attributed to no-till production systems are indeed realized.

What then is the most limiting factor restricting further development of landscape management strategies? In my opinion, it is a continued focus on individual problems or goals. Every issue has important aspects that must be rigorously investigated, understood, and advocated for, but for complex and "wicked" problems such as sustainable bioenergy feedstock development, air quality, water quality, soil quality, wildlife, carbon sequestration, rural development, residual or waste streams, and many others, the critical factors cannot be evaluated singularly, but must be addressed as an integrated system. As illustrated by the case study using the residue "tool," this is not an impossible task or a nirvana state of mind as the USDA NRCS has already developed soil-water-air-plant-animal + energy + human factor guidelines for their Field Office Guide. This (SWAPA + E + H) approach for land use assessment has been available for comprehensive farm planning since 1993. The key is recognizing and capitalizing on nature's diversity rather than trying to impose a "one-size fits all" model on living, dynamic systems.

References

Brick, S. 2011. Harnessing the Power of Biomass Residuals: Opportunities and challenges for Midwestern renewable energy. Heartland Papers. Issue 4. *Chicago Council on Global Affairs*, Chicago, IL.Bete, S.S. 2010. Taking conservation seriously as a wicked problem. In: P. Nowak and M. Schnepf (eds.) Managing Agricultural Landscapes for Environm*ental Quality II. Achieving more* effective conservation. *Soil and Water Conservation Society*, Ankeny, IA.

Rosillo-Calle, F. and F.X. Johnson (eds.). 2010. Food versus Fuel: An informed introduction to biofuels. *Palgrave Macmillan*, 175 Fifth Ave., N.Y. *217 pp.*

Wilhelm, W.W., J.R. Hess, D.L. Karlen, J.M.F. Johns*on, D.J. Muth, J.M. Baker, H.T. Gol*lany, J.M. Novak, *D.E. Stott, and G.*E. Varvel. 2010. Balancing Limiting Factors and Economic Drivers for Sustainable Midwest Agricultural Residue Feedstock Supplies. *Industrial Biotech*nology 6:271-287.

Volk, T. A., M. A. Buford, B. Berguson, J. Caputo, J. Eaton, J. H. Perdue, T. G. Rials, D. Riemenschneider, B. Stanton, and J. A. Stanturf. 2011. Woody Feedstocks – Management and regional differences. pp. 99-120. In: *In*: Braun, R., Karlen, D.L. and Johnson, D. (eds.) Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions. Proceedings of the Sustainable Feedstocks for Advanced Biofuel Workshop. Sept. 27-29, 2010. Atlanta, GA. Soil and Water Conservation Society, Ankeny, IA. (available online at: www.swcs.org/roadmap)

Muth, D. J. Jr. 2012. An investigation of sustainable agricultural residue availability for energy applications. Ph.D. Dissertation. *Iowa State University*, Ames, IA. 205 pp.

U.S. Department of Energy (DOE). 2011. U.S. Billion-Ton Update: Biomass supply for a bioenergy and bioproducts industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. *Oak Ridge National Labortory*, Oak Ridge, TN. 227 pp.

Conservation Technology Information Center (CTIC). 2002. Tillage type definitions. *CTIC*. Available on-line at: http://www.ctic.purdue.edu/resourcedisplay/322/

Holtman, K. M., D. V. Bozzi, D. Franqui- Villanueva, and W. J. Orts. 2011. Biofuels and bioenergy production forom municipal solid waste commingled with agriculturally-derived biomass. pp. 237-246. *In*: Braun, R., Karlen, D.L. and Johnson, D. (eds.) Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions. Proceedings of the Sustainable Feedstocks for Advanced Biofuel Workshop. Sept. 27-29, 2010. Atlanta, GA. *Soil and Water Conservation Society*, Ankeny, IA. (available online at: www.swcs.org/roadmap)

Karlen, D. L. 2011. Potential Soil Quality Impact of Harvesting Crop Residues for Biofuels. *Agrociencia Uruguay* 15(2):120-127.

Karlen, D.L., G. E. Varvel, J. M. F. Johnson, J. M. Baker, S. L. Osborne, J. M. Novak, P. R. Adler, G. W. Roth, and S. J. Birrell. 2011. Monitoring Soil Quality to Assess the Sustainability of Harvesting Corn Stover. *Agronomy Journal* 103:288–295.

Karlen, D.L., S. J. Birrell, and J. R. Hess. 2011. A Five-Year Assessment of Corn Stover Harvest in Central Iowa, USA. *Soil Tillage Research* 115–116: 47–55.