Potential Soil Quality Impact of Harvesting Crop Residues for Biofuels

Karlen Douglas L.[1]

[1]*USDA Agricultural Research Service (ARS) National Laboratory for Agriculture and the Environment (NLAE)*
2110 University Boulevard, Ames, IA 50011-3120, United States of America.
E-mail: Doug.Karlen@ars.usda.gov

Recibido: 31/3/11 Aceptado: 14/9/11

Summary

We are in one of the greatest technological, environmental and social transitions since the industrial revolution, as we strive to replace fossil energy with renewable biomass resources. My objectives are to (1) briefly review increased public interest in harvesting crop residues as feedstock for bioenergy, (2) discuss the work soil scientists must do to address those interests, and (3) examine how soil quality assessment can be used to help quantify soil biological, chemical and physical response to this transition. Rising global energy demand, dependence on unstable imports, volatility in price, and increasing public concern regarding fossil fuel combustion effects on global climate change are among the factors leading to an increased interest in development and use of renewable biomass sources for energy production. Although controlling soil erosion by wind and water is no less important than in the past, it is not the only factor that needs to be considered when evaluating the sustainability of land management practices including harvest of crop residues as bioenergy feedstock. The concept of soil quality assessment is reviewed and the Soil Management Assessment Framework (SMAF) is used to illustrate how such assessments can be used for assessing impacts of harvesting crop residue as feedstock for bioenergy production. Preliminary results of the SMAF assessment show that soil organic carbon (SOC) is one of the lower scoring indicators and therefore needs to be monitored closely. Innovative soil and crop management strategies, including a landscape vision are offered as ideas for achieving sustainable food, feed, fiber, and energy production.

Key words: bioenergy, soil management assessment framework (SMAF), renewable energy assessment project (REAP)

Resumen

Impacto potencial de la cosecha de residuos para biocombustibles sobre la calidad del suelo

Vivimos una de las mayores transiciones tecnológicas, ambientales y sociales desde la revolución industrial, en que nos esforzamos por sustituir la energía fósil con recursos de biomasa renovable. Mis objetivos son (1) reseñar brevemente el interés público en la recolección de los residuos de cultivos como materia prima para bioenergía, (2) discutir el trabajo que los científicos del suelo deben realizar para hacer frente a esos intereses, y (3) examinar la forma en que la evaluación de la calidad del suelo se puede utilizar para ayudar a cuantificar la respuesta biológica, química y física del suelo a esta transición. La creciente demanda mundial de energía, la dependencia de importaciones inestables, la volatilidad de los precios, y la creciente preocupación pública con respecto al uso de combustibles fósiles y sus efectos sobre el cambio climático mundial, son algunos de los factores que conducen a un mayor interés en el desarrollo y uso de fuentes renovables de biomasa para la producción de energía. Aunque el control de la erosión del suelo por viento y agua no es menos importante que en el pasado, no es el único factor que debe tenerse en cuenta al evaluar la sostenibilidad de las prácticas de manejo del suelo, incluida la recolección de residuos de cultivos como materia prima para la bioenergía. Se revisa aquí el concepto de evaluación de la calidad del suelo, y se usa el marco de evaluación del manejo de suelos (SMAF) para ilustrar cómo estas evaluaciones se pueden utilizar para evaluar los impactos de la recolección de residuos de cultivos como materia prima para la producción de bioenergía. Los resultados preliminares de la evaluación SMAF muestran que el carbono orgánico del suelo (SOC) es uno de los indicadores de puntuación más baja y por lo tanto debe vigilarse estrictamente. Estrategias innovadoras de manejo de suelos y cultivos, incluyendo una visión del paisaje, se ofrecen como ideas para lograr la producción sostenible de alimentos, forrajes, fibra y energía.

Palabras clave: bioenergía, evaluación del manejo de suelos, evaluación de energías renovables (REAP)

Introduction

The Global Challenge

A recent report by the US National Academy of Science (National Academy of Science, 2009) stated that world demand for energy has been increasing steadily, especially in developing nations such as China, where prior to the recent global economic recession double-digit increases in economic growth and energy consumption were the norm. It also pointed out that US dependence on foreign oil imports has increased from 40% to 56% since 1990, and that the long-term reliability of traditional sources for those oil inputs is uncertain because of political instability and resource limitations. Coupled with rising concerns regarding the effects of fossil-fuel combustion on global climate change and the volatility of energy prices, development and use of renewable biofuels has received an increasing amount of attention during the past decade.

Many factors and government policies in the US and abroad have been and will continue to influence the energy transition process. Answering questions regarding how we generate, supply, distribute and use energy will involve a complex mix of scientific, technical, economic, social, and political elements that will undoubtedly require decades to complete. Therefore, some have equated this transition to changing the course of a massive ship (National Academy of Science, 2009). One part of this transition is the increased interest in using renewable biomass sources as feedstock for both direct combustion and different types of biofuel. As a result, we in agriculture, especially those who understand soil resources, tillage systems, and other crop production factors, will have a very important role. Our knowledge, skill and ability to recognize and understand the fragile balance among economic, environmental and social factors that will be required to develop, produce, harvest, store, and transport renewable plant biomass to many different types of conversion facilities.

Agricultural scientists are well positioned for this challenge because of experience in developing, producing, harvesting and transporting food, feed and fiber resources to consumers around the globe. We also have the knowledge provided by our mentors (e.g. Larson *et al.*, 1972; Power and Legg, 1978; Elliott *et al.*, 1978; Larson, 1979) and from our own studies (e.g. Karlen *et al.*, 1984) following the first US energy crisis during the 1970s. Collectively, those and many other studies (e.g. Gollany *et al.*, 1991; Mann *et al.*, 2002; Liebig *et al.*, 2005; Moebius-Clune *et al.*, 2008) document effects of soil and crop management on soil erosion, SOC, and productivity that must be recognized to understand the complexity associated with harvesting crop residues and other lignocellulosic materials as feedstock for bioenergy. The studies also show that SOC is one of the most useful indicators available at this time for evaluating soil quality and future productivity (Shukla *et al.*, 2006), and have collectively led to the development of methodologies and databases by Johnson *et al.* (2006a, 2006b) that were used to estimate the amount of crop residue required to maintain SOC at current levels. Those findings were subsequently used by Wilhelm *et al.* (2007), who found that, in many cases, the amount of crop residue needed to maintain SOC (and thus soil productivity) is often far greater than the amount of crop residue needed to simply control wind and water erosion (Figure 1).

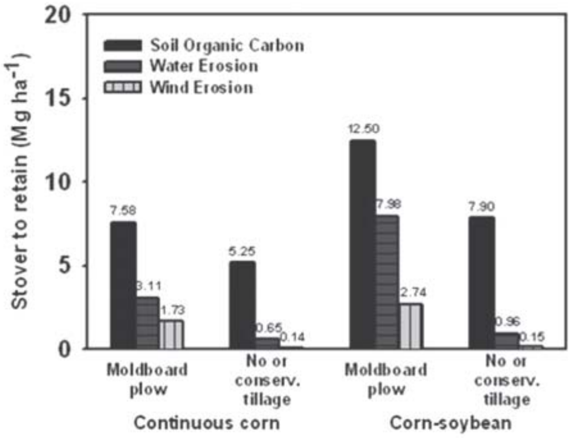

Figure 1. Tillage and crop rotation effects on the annual average amount of corn stover required to protect soil resources against wind or water erosion and to sustain soil carbon (organic matter) levels (Reprinted with permission from Wilhelm *et al*., 2007).

In the Billion Ton Report (BTR), Perlack *et al.* (2005) estimated that about 176 million Mg of biomass could currently be harvested from US agricultural lands without negatively impacting current agricultural markets or crop production. With technology advancements, adapted tillage practices, and carefully orchestrated land-use changes, they estimated that amount of harvestable biomass could be increased fivefold within 35 to 40 years. The largest agricultural source of that biomass was from annual crop residues, with corn (*Zea mays*) stover providing 75% of the total (Nelson, 2002). Stover is most available in the US Corn/Soybean Belt where approximately 21 million ha of corn is cultivated annually, producing an estimated 163 million Mg of total residue (NASS, 2009).

With current collection technology, about 40% of the crop residue (Patterson, 2003; Grant *et al.,* 2006; Shinners and Binversie, 2007) can be collected, but with the development of single-pass harvest technologies it will be mechanically possible to collect more than 70% residue (Shinners *et al.,* 2007). However, from a soils perspective, studies have shown that sustainable residue removal rates are extremely site sensitive, and to maintain SOC, while also preventing erosion, compaction, excessive plant nutrient loss, and other environmental degradation (Figure 2), guidelines and innovative practices will be needed (Nelson, 2002; Wilhelm *et al.,* 2004; Sheehan *et al.,* 2004; Johnson *et al.,* 2006b; Hoskinson *et al.*, 2007).

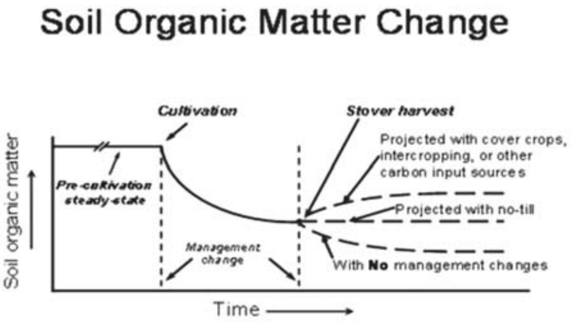

Figure 2. During the first 50 years after converting native prairie or forest to production agriculture, 20 to 50% of the original, steady-state soil organic matter was lost. Harvesting crop residues without changing other practices will result in further SOC decline.

Having established the need for sustainable feedstock production and harvest strategies, the remainder of this work will focus on our USDA-Agricultural Research Service (ARS) Renewable Energy Assessment Project (REAP) research.

Methodology

Renewable Energy Assessment Project (REAP) Research

The BTR emphasis on crop residues, especially corn stover, raised concern among many soil scientists who feared that without sustainability guidelines excessive removal could degrade soil quality and reduce crop yield (Wilhelm *et al.*, 1986, 2004). As shown in Figure 2, harvesting corn stover for any purpose without offsetting practices will decrease annual carbon input, slowly diminish SOC levels, and thus threaten the soil's production capacity (Mann *et al.*, 2002; Johnson *et al.*, 2006a). These concerns were accentuated because many soils where corn is produced have artificial drainage, intensive annual tillage, and less diverse plant communities-factors that have already reduced SOC by 30 to 50% when compared to pre-cultivation levels (Schlesinger, 1985).

To address the need for sustainable guidelines regarding harvest of all types of crop residues, the ARS developed a multi-location REAP team in 2006 that involved 14 scientists from nine locations; an effort that now involves more than 25 ARS locations. The research objectives were to:

1. Determine the amount of crop residues (e.g., corn stover, cover crop) that must remain on the land to maintain soil organic carbon and sustain production;
2. Estimate the trade-off between the short-term economic return to growers who harvest crop residues as biofuel or biomass product feedstock versus the long-term benefits to soil, water, and air resources associated with retaining crop residues to build soil organic matter and sequester carbon;
3. Develop robust algorithm(s) to guide the amount of crop residue that can be sustainably harvested as feedstock for biomass ethanol and bio-based products without degrading the soil resource, environmental quality, or productivity; and
4. Develop management strategies (e.g., no tillage) supporting sustainable harvest of residue. Modify existing or devise new management practices that allow harvest of stover but maintain production level and soil organic carbon through use of cover crops, organic amendment, or other techniques.

Using new and on-going field studies, a Regional Partnership[1] was developed with university colleagues in six states to help achieve these objectives. Soil quality assessment was chosen to help assess the soil resource impact of harvesting corn stover. The SMAF, developed by Andrews *et al.* (2004) and used to evaluate chemical, physical and biological responses to various land uses, farming systems and management practices (Karlen *et al.*, 1997, 2006; Liebig *et al.*, 2006; Wienhold *et al.*, 2006; Zobeck *et al.*, 2008; Jokela *et al.*, 2009), was used to evaluate soil quality effects. By focusing on soil quality, the REAP team desired to help change perceptions that crop residues are not important for modern grain production systems.

A common, continuous corn experiment, using no-tillage, three rates of stover harvest [none, high-cut, and low-cut), and four replications was established at each site. Other treatments as appropriate for each location (e.g. cover crops, biochar application, conventional tillage, twin-row high population systems) were also evaluated. To provide a baseline, composite soil samples were collected to a depth of 1 m using increments of 0 to 5, 5 to 15, 15 to 30, 30 to 60 and 60 to 90 cm prior to harvesting any stover. Samples were analyzed for pH, electrical conductivity (EC), total organic carbon (TOC), and several soil fertility indicators using routine soil-test procedures (NCR, 1998).

To illustrate use of the SMAF for soil quality assessment, five measurements that were available from six of the Partnership locations were used for an initial analysis. The SMAF released in 2004 (Andrews *et al.*, 2004) had scoring functions for 11 potential soil quality indicators. Recently, scoring functions for water-filled pore space, soil-test K, and the enzyme â-glucosidase were added (Wienhold *et al.*, 2009; Stott *et al.*, 2010) to the framework. Most studies do not have data for all 14 indicators so a general guideline of using five indicators, with at least one representing biological, chemical, and physical soil properties and processes (Karlen *et al.*, 2007), has been applied to various studies.

Discussion

Data in Table 1 show the results for analyses performed for the 0 to 5 and 5 to 15 cm depth increments. Based on the five indicators, all sites except Mead, NE had an index score of 0.7 to 0.75 for the surface 5 cm and 0.6 to 0.7 for the 5 to 15 cm depth. This means the soils at the sites being used for the field studies are functioning at about 75% of their inherent potential with regard to TOC. The Mead site had index values of 0.58 and 0.57 for the two depths, primarily because TOC values were very low compared to inherent levels associated with the Aksarben silt loam soil. Low TOC at Mead presumably also contributed to the low bulk density score for both depth increments because of the role soil organic matter has in sustaining soil structure. From a fertility or chemical perspective, soil at the Mead site had a good quality.

---

[1] Funded in part by the North Central Regional Sun Grant Center at South Dakota State University through a grant provided by the US Department of Energy Office of Biomass Programs under award number DE-FC36-05GO85041.

Table 1. Baseline soil quality indicator scores and the overall SMAF index for sites used to quantify effects of harvesting corn stover as a bioenergy feedstock. TOC: Total Organic Carbon, P: Phosphorus, K: Potassium, BD: Bulk Density, SQI: Soil Quality Indicator

Location	Indicator Scores					SQI
	TOC	pH	P	K	BD	
			0 to 5 cm depth			
Ames, IA	0.71	1.00	1.00	0.99	0.90	0.74
Brookings, SD	0.77	1.00	1.00	0.92	0.89	0.74
Florence, SC	0.92	0.99	1.00	0.52	0.72	0.69
Morris, MN	0.71	1.00	1.00	0.88	0.87	0.72
Mead, NE	0,37	0.94	1.00	0.61	1.07	0.58
University Park, PA	0.85	0.99	0.85	0.97	1.05	0.73
			5 to 15 cm depth			
Ames, IA	0.57	1.00	1.00	0.99	0.79	0.71
Brookings, SD	0.61	0.99	0.98	0.65	0.83	0.65
Florence, SC	0.82	1.00	1.00	0.36	0.58	0.63
Morris, MN	0.41	1.00	0.97	0.80	0.77	0.64
Mead, NE	0.26	0.95	0.90	0.75	1.06	0.57
University Park, PA	0.27	1.00	1.00	0.83	0.99	0.62

The amount of data available for this initial SMAF analysis is very limited, so it's important to be cautious with any interpretations, but overall, it appears that TOC is the factor that needs to be improved the most. At the Florence site, soil-test K in the 5 to 15 cm increment had a score of 0.58 indicating it should be increased, but because of the type and low amount of clay in this soil, this change will not be very feasible until TOC and the associated cation exchange capacity is increased (Karlen *et al.*, 1984; Hunt *et al.*, 1996). The bulk density score for the 5 to 15 cm increment at Florence was also quite low, but this was not unexpected considering soils in this area have very well-defined eluvial (E) horizons that generally require in-row tillage to physically disrupt them on an annual basis (Busscher *et al.*, 1986).

The SMAF analyses support a general hypothesis that to develop sustainable feedstock production strategies, annual carbon (C) input must be accurately estimated. As a starting point, Johnson *et al.* (2006a) used empirical data and linear regression to correlate C inputs to SOC and proposed *minimum source C* (MSC) as a term to describe the annual C input needed to ensure no net change in SOC content. Since the initial review, results from several other studies have been added to the database being used for MSC estimates (Johnson *et al.,* 2009). Using above-ground non-grain C inputs, MSC was calculated at 2.5 ± 1.7 Mg C ha^{-1} yr^{-1} (n = 28) for different crop and tillage practices. This was slightly higher than the original MSC value of 2.2 ± 1.1 Mg C ha^{-1} yr^{-1} (n = 21). The new studies confirmed that moldboard plow systems had higher MSC requirements than those with no tillage and agreed with findings by Bayer *et al.* (2006). Assuming a C concentration of 400 g kg^{-1} (40%) in corn stover, 6.25 Mg ha^{-1} yr^{-1} of residue must be left in the field to supply the average MSC (2.5 Mg C ha^{-1} yr^{-1}). This agrees with the value of 6 Mg ha^{-1} of corn stover reported by Larson *et al.* (1972) as the amount required for sustaining SOC levels.

In general, there are two basic methods to avoid SOC loss: (1) decrease output (*i.e*. return all crop residues to the land) or (2) increase input (*i.e*. increase the amount of organic substrates available to the system). The first, limiting removal of crop residues may be effective for maintaining soil quality but it does not address the reality of meeting needs of an emerging biofuel market that will directly compete for these resources. This emphasizes the importance of quantifying soil quality impact of stover harvest, so that in some areas producers will be able to redirect a portion of their crop residue to these new markets without negatively impacting their long-term productivity and economic viability.

The second method to avoid SOC loss is to increase carbon inputs. This is the ultimate long-term solution to both maintain soil productivity *and* produce sufficient yields of biomass to support a biofuel industry (Fales *et al.*, 2007; Johnson *et al.*, 2007). The long-term goal must be to maximize the capture and use of light and CO_2 available on every unit of arable land and strive to use the resulting crop dry matter in the most appropriate manner. Crabtree and Lewis (2007) estimated that in one hour the sun delivers to the earth the amount of energy used by humans each year. Obviously, not all this energy can be captured in the form of plant biomass, but opportunities exist for improving our efficiency in capturing and using solar energy. To achieve the goal of vastly increased capture of solar radiation and production of reduced C, a series of technologies must be applied. Some of these technologies already exist, but others have yet to be developed.

Existing techniques (i.e., adding cover crops to the crop sequence and using planting times and patterns that maximize solar radiation interception) can be deployed in the near term to reap immediate gains in C input to the system. Other techniques must be refined before deployment (*e.g.* sensor-driven application of inputs [nutrients and pesticides] based on crop need). Changes in crop genetics and production practices that seem visionary or pioneering today (i.e., developing canopies with structures that result in greater penetration of light to lower leaves, increasing the efficiency of the carbon fixation enzymes, and reduction of photorespiration), will be developed and honed for application in out years (Long *et al.*, 2006). The goal of these efforts is not to increase the demand for existing resources, but to optimize the use of existing resources and increase the sustainable productivity of all resources so that there are sufficient quantities to meet increasing demands for food, feed, fiber, *and* biofuels.

A Landscape Vision

One approach that could be used to help address several critical issues, including supplying feedstock for bioenergy, decreasing nutrient loss to surface and ground water resources, sequestering carbon, providing improved food and habitat for wildlife, enhancing soil quality, and revitalizing rural communities, is to create a diversified landscape by incorporating annual, perennial, and inter-cropping mixtures into future farming operations. Implementing a landscape-scale vision would also address many concerns regarding productive capacity and the need for increased primary production to support a biofuels industry (e.g., Doornbosch and Steenblik, 2007; Ernsting and Boswell, 2007; Fargione *et al.,* 2008; Searchinger *et al.,* 2008).

To understand the sustainable landscape vision, it is important to recognize that agriculture is more than farms, farmers, and commodity crops {corn, soybean [*Glycine max* (L.) Merr.], wheat (*Triticum aestivum* L.), cotton (*Gossypium* spp.), rice (*Oryza sativa* L.) and sugarcane (*Saccharum* spp.)}. Developing lignocellulosic feedstocks and biofuel enterprises within definable watersheds could provide several unique opportunities to more fully integrate economic, environmental, and social aspects of agriculture into integrated systems. By planning to harvest only in areas where the amount of crop residue exceeds that required to maintain soil resources (Lal, 2006) and striving to develop dedicated bioenergy crops, agriculture as a system could help mitigate increased nitrate (NO_3-N) concentrations in streams and groundwater, the need for dredging of sediments, and potential hypoxia problems.

By using biofuel feedstock production as the economic driver, many ecosystem services could be captured through implementation of a landscape management plan that includes establishing woody species as buffers near streams and long-term perennial biomass crops at slightly higher landscape positions (National Academy of Science, 2009). These vegetative buffers could reduce leaching of NO_3-N and runoff of soluble phosphorus (P) while sequestering carbon (C) for several months before being harvested as feedstocks during their dormant period. Slightly higher on the landscape, diverse perennial mixtures of warm season grasses and cool season legumes could produce biomass and store organic carbon in soils. In autumn, these perennials would provide a source of biomass, providing at least three landscape management benefits (biomass production, C sequestration, and water quality). Further up the landscape, a diversified rotation of annual and perennial crops would be used to meet food, feed, and fiber needs. Erosion could be partially mitigated by using cover crops and/or living mulches. Intensive row crop production areas could be established using best management practices (BMPs); if fertilizer recovery was less than desired, there would be substantial buffer areas at lower landscape positions to capture residual nutrients and sediment.

Currently, this landscape vision is conceptual, but calculations based on a recent US study in Iowa suggest that converting just 10% of a watershed from no-tillage corn and soybean to strips of herbaceous perennial plants could decrease water runoff by 49% and sediment export by 96%, while simultaneously increasing native plant, bird, and beneficial insect populations (Helmers and Asbjornsen, 2011). This confirms that understanding complex interactions between economics, soil and crop management decisions, productivity, and environmental consequences can result in agricultural systems that would meet global food, feed, fiber and fuel demands in a truly sustainable manner.

Conclusions

Global development of biofuel production systems appears to be immanent for multiple reasons including increasing demand for finite fossil fuel supplies and rising concern regarding CO_2 emissions. Plants, because of their ability to capture and use CO_2 and light to produce renewable feedstock and soils because they provide the water and nutrients needed to sustain plant growth provide the foundation for our future. This presentation summarizes my current research activities and thinking with regard to how soil quality and biomass production must be viewed simultaneously to achieve truly sustainable agricultural production systems.

References

Andrews SS, Karlen DL, Cambardella CA. 2004. The soil management assessment framework : a quantitative soil quality evaluation method. *Soil Science Society of America Journal,* 68: 1945 - 1962.

Bayer C, Lovato T, Dieckow J, Zanatta JA, Mielniczuk J. 2006. A method for estimating coefficients of soil organic matter dynamics based on long-term experiments. *Soil and Tillage Research,* 91: 217 – 226.

Busscher WJ, Sojka RE, Doty CW. 1986. Residual effects of tillage on coastal plain soil strength. *Soil Science,* 141: 144 - 148.

Crabtree GW, Lewis NS. 2007. Solar energy conversion. *Physics Today*, 60: 37 - 42.

Doornbosch R, Steenblik R. 2007. Biofuels : Is the cure worse than the disease? Paris : OECD. 57p. (SG/SD/RT; 3).

Elliott LF, McCalla TM, Waiss A. 1978. Phytotoxicity associated with residue management. In: Oschwald WR. [Ed.] Crop Residue Management Systems. Madison: American Society of Agonomy. (ASA Special Publication; 31). pp. 131 - 146.

Ernsting A, Boswell A. 2007. Agrofuels : Towards a reality check in nine key areas [On-line]. Cited 26 August 2011. Available from: http://www.carbontradewatch.org/pubs/Agrofuels.pdf.

Fales SL, Hess JR, Wilhelm WW. 2007. Convergence of agriculture and energy : II Producing cellulosic biomass for biofuels. Ames : Council for Agricultural Science and Technology (CAST). 8p. (CAST Commentary; QTA2007-2).

Fargione J, Hill J, Tillman D, Polasky S, Hawthorne P. 2008. Land clearing and the biofuel carbon debt. *Science*, 319(5867): 1235 – 1238.

Gollany HT, Schumacher TE, Evenson P, Lindstrom MJ, Lemme GD. 1991. Aggregate stabilitystability of an eroded and desurfaced desurfaced typic Argiustoll. *Soil Science Society of America Journal*, 55: 811 - 816.

Grant D, Hess JR, Kenney K, Laney P, Muth D, Pryfogle P, Radtke C, Wright C. 2006. Feasibility of a producer-owned ground-straw feedstock supply system for bioethanol and other products. Idaho : INL. 115p.

Helmers M, Asbjornsen H. 2011. Ecohydrological Response to Integrating Perennial Vegetation into Midwestern Agricultural Landscapes : What We Are Doing [On-Line]. Cited 25 October 2011. Available from: http://www.nrem.iastate.edu/research/STRIPs/research/index.php?page=Ecohydrological.

Hoskinson RL, Karlen DL, Birrell SJ, Radtke CW, Wilhelm WW. 2007. Engineering, nutrient removal and feedstock conversion evaluations of four corn stover harvest scenarios. *Biomass & Bioenergy*, 31: 126 - 136.

Hunt PG, Karlen DL, Matheny TA, Quisenberry VL. 1996. Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. *Journal of Soil and Water Conservation*, 51: 255 - 258.

Johnson JMF, Papiernik SK, Mikha MM, Spokas K, Tomer MD, Weyers SL. 2009. Soil Processes and Residue Harvest Management. In: Lal R, Steward B. [Eds.] Carbon Management, Fuels, and Soil Quality. New York : Taylor and Francis. pp. 1-44.

Johnson JMF, Coleman MD, Gesch R, Jaradat A, Mitchell R, Reicosky D, Wilhelm WW. 2007. Biomass-bioenergy crops in the United States : A changing paradigm. *Americas Journal of Plant Science and Biotechnology*, 1: 1 - 28.

Johnson JMF, Allmaras RR, Reicosky DC. 2006a. Estimating source carbon from crop residues, roots, and rhizodeposits using the national grain-yield database. *Agronomy Journal*, 98: 622 - 636.

Johnson JMF, Reicosky D, Allmaras R, Archer D, Wilhelm WW. 2006b. A matter of balance: Conservation and renewable energy. *Journal of Soil and Water Conservation*, 61: 120A - 125A.

Jokela WE, Grabber JE, Karlen DL, Balser TC, Palmquist DE. 2009. Cover Crop and Liquid Manure Effects on Soil Quality Indicators in a Corn Silage System. *Agronomy Journal*, 101: 727 – 737.

Karlen DL, Zobeck TM, Wienhold BJ. 2007. Soil quality assessment – a value added opportunity for soil testing laboratories. In: Warncke D. [Ed.]. Proceedings of the 18th Soil/Plant Analysts Workshop; February 27-28, 2007; Bettendorf, Iowa, United State. Michigan : Michigan State University. (North Central Extension and Research Activity ; 13). pp. 63 - 69.

Karlen DL, Hurley EG, Andrews SS, Cambardella CA, Meek DW, Duffy MD, Mallarino AP. 2006. Crop rotation effects on soil quality at three northern corn/soybean belt locations. *Agronomy Journal*, 98: 484 - 495.

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. 1997. Soil quality : A concept, definition, and framework for evaluation. *Soil Science Society of America Journal*, 61: 4 - 10.

Karlen DL, Hunt PG, Campbell RB. 1984. Crop residue removal effects on corn yield and fertility of a Norfolk sandy loam. *Soil Science Society of America Journal*, 48: 868 - 872.

Lal R. 2006. Managing soils to feed a global population of 10 billion. *Journal of the Science of Food and Agriculture*, 86: 2273 – 2284.

Larson WE. 1979. Crop residues : Energy production or erosion control. *Journal of Soil and Water Conservation*, 34: 74 - 76.

Larson WE, Clapp CE, Pierre WH, Morachan YB. 1972. Effect of increasing amounts of organic residues on continuous corn : II. Organic carbon, nitrogen, phosphorus, and sulfur. *Agronomy Journal,* 64: 204 – 208.

Liebig MA, Carpenter-Boggs L, Johnson JMF, Wright S, Barbour N. 2006. Cropping system effects on soil biological characteristics in the Great Plains. *Renewable Agriculture and Food Systems*, 21: 36 - 48.

Liebig MA, Morgan JA, Reeder JD, Ellert BH, Gollany HT, Schuman GE. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil and Tillage Research*, 83: 25 - 52.

Long SP, Zhu X-G, Naidu SL, Ort DR. 2006. Can improvement in photosynthesis increase crop yields? *Plant, Cell & Environment*, 29: 315 - 330.

Mann L, Tolbert V, Cushman J. 2002. Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on soil organic matter and erosion. *Agriculture, Ecosystems & Environment.*, 89: 149 - 166.

Moebius-Clune BN, Es HM van, Idowu OJ, Schindelbeck RR, Moebius-Clune DJ, Wolfe D, Abawi G, Thies J, Gugino B, Lucey R. 2008. Long-term effects of harvesting maize stover and tillage on soil quality. *Soil Science Society of America Journal*, 72: 960 - 969.

NASS. 2009. Data and Statistics [On-line]. Washington : USDA. Cited 26 March 2010. Available from: http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp.

National Academy of Science. 2009. America's energy future: Technology and transformation. Washington : National Academies Press. 711p.

NCR. 1998. Recommended chemical soil test procedures for the North Central Region. Columbia : Missouri Agricultural Experiment Station. 72p. (North Central Regional Research Publication ; 221).

Nelson RG. 2002. Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States—rainfall and wind-induced soil erosion methodology. *Biomass and Bioenergy*, 22: 349 - 363.

Patterson PE. 2003. Availability of straw in eastern Idaho[On-line]. Cited 18 August 2011. Available from: http://www.cals.uidaho.edu/aers/PDF/ProjReport/Straw_Availability_Revised_Report.pdf.

Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC. 2005. Biomass as feedstock for a bioenergy and bioproducts industry : The technical feasibility of a billion-ton annual supply [On-line]. Cited 26 March 2010. Available from: http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf.

Power JF, Legg JO. 1978. Effect of crop residues on the soil chemical environment and nutrient availability. In: Oschwald WR. [Ed.]. Crop Residue Management Systems. Madison : ASA. (ASA Spec. Publ.; 31). pp. 85 - 100.

Schlesinger WH. 1985. Changes in soil carbon storage and associated properties with disturbance and recovery. In: Trabalha JR, Reichle DE. [Eds.]. The changing carbon cycle : A global analysis. New York : Springer-Verlag. pp. 194 – 220.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T-H. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science*, 319(5867): 1238 – 1240.

Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, Nelson R. 2004. Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology*, 7: 117 - 146.

Shinners KJ, Binversie BN. 2007. Fractional yield and moisture of corn stover biomass produced in the northern US corn belt. *Biomass and Bioenergy*, 31: 576 - 584.

Shinners KJ, Boettcher GC, Munk JT, Digman MF, Muck RF, Weimer PJ. 2007. Single-pass, split-stream of corn grain and stover : characteristic performance of three harvester configurations. *Transactions of the American Socity of Agriculutural and Biological Engineers*, 50(2): 355 - 363.

Shukla MK, Lal R, Ebinger M. 2006. Determining soil quality indicators by factor analysis. *Soil and Tillage Research*, 87: 194 - 204.

Stott DE, Andrews SS, Liebig MA, Wienhold BJ, Karlen DL. 2010. Evaluation of â-Glucosidase activity as a soil quality indicator for the soil management assessment framework (SMAF). *Soil Science Society of America Journal*, 74: 107 - 119.

Wienhold BJ, Karlen DL, Andrews SS, Stott DE. 2009. Protocol for indicator scoring in the soil management assessment framework (SMAF). *Renewable Agriculture and Food Systems*, 24: 260 - 266.

Wienhold BJ, Pikul JL, Liebig MA, Mikha MM, Varvel GF, Doran JW, Andrews SS. 2006. Cropping system effects on soil quality in the Great Plains : Synthesis from a regional project. *Renewable Agriculture and Food Systems.*, 21: 49 - 59.

Wilhelm WW, Johnson JMF, Karlen DL, Lightle DT. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, 99: 1665 – 1667.

Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR. 2004. Crop and soil productivity response to corn residue removal : A literature review. *Agronomy Journal*, 96: 1 - 17.

Wilhelm WW, Doran JW, Power JF. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. *Agronomy Journal*, 78: 184 - 189.

Zobeck TM, Halvorson AD, Wienhold BJ, Acosta Martinez V, Karlen DL. 2008. Comparison of two soil quality indexes to evaluate cropping systems in northern Colorado. *Journal of Soil and Water Conservation*, 63: 329 – 338.