White Paper

Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations

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Executive Summary

In light of the renewed interested in domestic production of biofuels and other biomass energy, can the more than 500 million tons of crop residue produced each year be used to meet some of our energy needs? The answer is not straightforward because residues perform many positive functions for agricultural soils. Recent studies and reviews attempt to address this issue. Despite some shortcomings, existing research can be used to guide practices to a great extent, especially for corn stover harvest in the Corn Belt, which has been studied most extensively. Specific guidelines for residue harvest need to be developed in an effort to prevent soil degradation resulting from over-harvest.

Soil quality effects:

- **Soil Erosion.** Surface residues protect soil from water and wind erosion. Residues also increase soil resistance to runoff events, unless soil infiltration is already impaired. Studies predict that up to 30% of surface residue can be removed from some no-till systems without increased erosion or runoff.
- **Organic Matter and Nutrients.** With added nitrogen fertilizers, residues can increase soil organic matter (SOM). However, roots appear to be the largest contributor to new SOM, making residues less important for carbon accrual. Residue removal leading to higher erosion and runoff rates would greatly decrease SOM and nutrients. Residue harvest would also require increased fertilizer inputs to make up for nutrients removed in the plant material.
- **Beneficial and Deleterious Soil Organisms**. Residue removal can result in detrimental changes in many biological soil quality indicators including soil carbon, microbial activity, fungal biomass and earthworm populations, indicating reduced soil function. Some disease-producing organisms are enhanced by residue removal, others by residue retention, depending on crop and region.
- **Available Water and Drought Resistance.** Residue cover can reduce evaporation from the soil surface, thereby conserving moisture and increasing the number of days a crop can survive in drought conditions. Improved soil physical properties related to crop residues, such as reduced bulk density and greater aggregate stability, also lead to better water infiltration and retention.
- **Soil Temperature and Crop Yield.** In colder climates, residues are linked to reduced yields due to lower soil temperatures resulting in poor germination. Stubble mulching, as opposed to residue chopping, can overcome this problem. Residue-associated yield reductions have also been found on poorly drained, fine–textured soils. Since these soils often have low erosion risk, residues might safely be removed.

Recommendations:

- **Residue Removal Rates.** Sustainable crop residue removal rates for biofuel production will vary by factors such as management, yield, and soil type. Tools like RUSLE, WEQ, and the Soil Conditioning Index are likely to be the most practical ways to predict safe removal rates. Removal rates are not the same as percent soil cover: appropriate conversion is necessary and will vary by crop and region. While areas with low slopes and high yields may support residue harvest, in many areas the residue amounts required for maintaining soil quality will be higher than current soil cover practices.
- **Additional Conservation Practices.** Conservation practices such as contour cropping or conservation tillage must be used to compensate for the loss of erosion protection and SOM reductions seen with residue removal. In many regions, cover crops are another viable alternative.
- **Crop Alternatives.** Crop residue biofuels may not be a viable option, energetically or economically. Several recent reviews found that the energy invested to produce the biofuel was not sufficiently greater than the quantity and quality of energy produced. A more viable option may be crops grown specifically for biofuels, including herbaceous energy crops like switchgrass and short-rotation woody crops like hybrid poplar.
- **Periodic Monitoring and Assessment**. Regardless of the residue removal practice chosen, fields should be carefully monitored for visual signs of erosion or crusting. Periodic checks of soil carbon as part of fertility testing are also recommended. Removal rates should be adjusted in response to adverse changes: if erosion increases or carbon decreases, removal rates must be reduced to maintain soil quality.

The Promise of Biomass Energy

Concerns about the security and sustainability of fossil fuel use, coupled with advances in biomass conversion technology, have renewed interest in crop residue as a biofuel to partially meet our energy needs (Glassner et al., 1999). *In light of this renewed interested in production of biofuels and other biomass energy, can the more than 500 million tons of crop residue produced each year be used to meet some of our energy needs?* The answer is not straightforward because residues perform many positive functions for agricultural soils. Numerous studies and reviews attempt to address this issue. Despite some shortcomings, existing research and models can be used to guide practices, especially for corn stover harvest in the Corn Belt, which has been studied most extensively. Specific guidelines for residue harvest must be developed if residues are to be used in a sustainable manner.

President Bush's (2006) State of the Union Address specifically targeted alternative sources for ethanol production (wood chips, stalks and switchgrass) for practicality and competitive (pricing) within the next 6 years. Leading up to this, crop residues as an inexpensive feedstock for bioenergy production have been a major object of study and consideration by researchers and industry. The US Department of Agriculture (USDA) is funding a number of projects under the Biomass Research and Development Initiative (a joint effort DOE and USDA) that specifically target crop residue harvest, pre-treatment or related issues for bioenergy production: 3 (of 13) funded projects in 2004 and 4 (of 11) in 2005. The DOE portion of the Initiative is also funding a number of projects examining novel conversion technologies for cellulosic materials, including crop residues.

The eight leading U.S. crops produce more than 500 million tons of residue each year (R.G. Nelson, personal communication, 2003). Some amount of this residue may be available for harvest and use as feedstock for biomass energy. Corn (*Zea mays* L.) (and to a lesser extent, wheat) is receiving the most attention due to its concentrated production area and because it produces 1.7 times more residue (or stover) than other leading cereals, based on current production levels (Wilhelm et al., 2004), sufficient quantity to support commercial scale production (DiPardo, 2000).

The low-cost and abundance of harvesting crop residues make them competitive as gasoline additives (DiPardo, 2000). In order to realize this low cost, however, most agree that one-pass harvest for grain and stover must become a reality (DOE, 2003). Once technology to produce ethanol from cellulosic materials is in place, it may be more efficient and the resultant fuel may have lower emissions than grain ethanol (Table 1). However, because residues perform many positive functions for soils in the agroecosystem; their removal must be considered carefully.

Table 1. Comparison of Corn Grain Ethanol and Corn Stover Ethanol.

Ethanol Feedstock	Net Energy Balance* ($e_{EtOH} - e_{production}$)	Percent reduction in GHG emissions/vehicle mile** E10	E85
Corn grain	25,000 Btu/gal	2%	25%
Corn stover	60,000 Btu/gal	9%	79%

*Net Energy Balance is estimated as the energy contained in 1 gallon of ethanol minus the energy required to produce it.

**Estimates of greenhouse gas (GHG) emissions from E10 (90:10 gasoline:ethanol) and E85 (15:85 gasoline:ethanol) as compared with conventional gasoline (Wang et al., 1999).

The Role of Crop Residues: Pros and Cons

Crop residues are generally thought to enhance and protect soil quality. Some general effects of crop residues left on the soil surface on soil functions include:

- **Protection from erosive forces**;
- **Increased or maintained soil organic matter**;
- **Additions to the available pool of soil nutrients**;
- **Increased biological activity and improved soil structure**; and
- **Improved crop yields** (Hargrove, 1991).

The basic relationships between these effects are shown in Table 2.

Table 2. General Benefits of Crop Residues to Soil Quality (after Larson, 1979)

Primary Effect		Secondary Effect		Tertiary Effect
Contributes to soil organic matter	⇨	Improves Chemical, Physical & Biological Properties	⇨	Increases yield and yield sustainability
Provides Physical buffer	⇨	Reduces raindrop impact and wind shear	⇨	Reduces soil erosion

Despite the many important benefits of crop residues, research shows their effects can vary. For instance, some reports showed lower yields in systems with high crop residues due to increased disease or poor germination (e.g. Linden et al., 2000); others reported higher yields when soil moisture is limiting (e.g. Power et al., 1986). Some studies suggested that residues do not contribute significantly to soil carbon (e.g., Gale et al., 2000). Many studies found that additional N fertilizer is needed when residues are left on soils to avoid N uptake (immobilization) from soil or allow for soil carbon accrual (e.g. Clapp et al., 2000). For appropriate residue removal recommendations, the conditions leading to these varied effects of residues must be elucidated.

In a review by five USDA Agricultural Research Service (ARS) scientists, Wilhelm et al. (2004) acknowledged the complexity of interactions between soil type, climate, and management when considering crop residue effects on soil. They recommended that removal rates be based on regional yield, climatic conditions and cultural practices, with no specific rates given. Using RUSLE technology, Nelson (2002) predicted safe residue removal rates for minimizing soil loss in the Eastern and Midwestern U.S. These predictions varied widely over time and location as a result of the complex interactions discussed by Wilhelm et al. (2004). In another recent review, sponsored by the U.S. Department of Energy (DOE), Mann et al. (2002) concluded that before specific recommendations could be made, more information was needed on the long term effects of residue harvest, including: 1) water quality; 2) soil biota; 3) transformations of different forms of soil organic carbon (SOC); and 4) subsoil SOC dynamics. Current USDA NRCS practice standards for residue management shy away from specific residue quantities and point to the use of the RUSLE2 model for guidance (without specifics on how to do so) (USDA-NRCS, 2005). Despite broad recognition of the need for specific guidelines for residue removal, none yet exist. This paper attempts to draw some conclusions from the current body of research and outline a general procedure for the development of harvest guidelines.

Residue Removal Research Considerations

Among U.S. crops, corn has the greatest potential for fuel production because of the large amount of residue it produces and its highly concentrated growth area in the Midwest. For this reason, most research has concentrated on the U.S. Corn Belt and seldom addressed other crops or regions.

Nevertheless, other high residue crops, such as rice and sugarcane, might contribute to biofuel production as a solution to their residue disposal issues (DiPardo, 2000; Wilhelm et al., 2004).

Most field and modeling research has compared no-till systems with residues to tilled systems without residues, overlooking the significant interaction effects between tillage and residues (Sauer et al., 1996). There is also a lack of studies examining the long-term effects of residue removal on soils (Mann et al., 2002). Early work relied heavily on predictive models, generally using USLE then EPIC (with RUSLE). Numerous authors have cited T values associated with USLE as a questionable upper limit for tolerable soil losses (e.g., Mann et al., 2002). This potentially serious shortcoming casts some doubt on the predicted effects of residue removal in many of the earlier studies. In addition, much of this work considered cropping systems that included low residue crops for harvest (e.g. Lindstrom et al., 1981). Low residue crops, such as soybean, rarely produce enough residue to maintain adequate soil cover through the winter and, therefore, none is available for harvest (Shelton et al., 1991). The low residue designation is not necessarily due to low production but more often to the fast decomposition of high quality (low C:N ratio) residues. It is insufficient to consider only residue quantity without regard to quality when determining potential harvest rates.

One practical difficulty in applying many research results is that most studies examine residue removal rates based on biomass or weight of tissues removed, while management practices and conservation programs concentrate on the percentage of soil covered by residue. This problem is relatively simple to overcome but potentially confusing. ***A 30% removal rate is not the same as 70% soil cover.*** The two are positively related but their exact relationship varies with crop residue quality, climate, soil type and management practices such as N fertilization rate. McCool et al. (1995) described the relationship between percent soil cover and residue removal rate for small grains and annual legumes in the non-irrigated US Northwest as an exponential association (Figure 1). While this particular relationship would only be valid for crops with similar C:N ratios grown under similar conditions, its exponential nature would likely hold true in a variety of systems. These relationships need to be defined or estimated for all candidate biofuel residue systems to accurately translate research findings into appropriate practice recommendations.

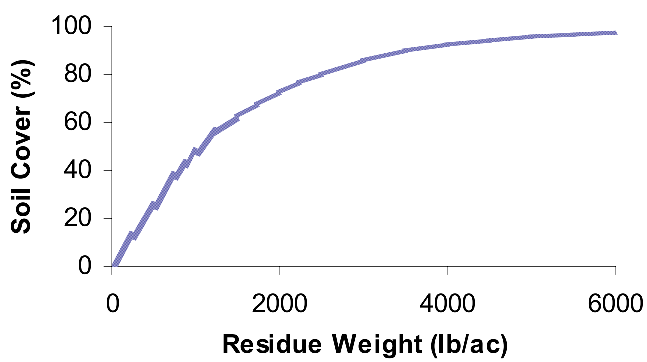


Figure 1. The exponential relationship between percent of soil covered by residues and residue weight per acre for common small grains and annual legumes in the non-irrigated US Northwest

The following brief review, organized by effect, will concentrate on those studies that are longer-term or attempted to account for tillage and residue interactions.

- **Erosion Control**

Erosion protection and the associated conservation of nutrients, organic matter, soil water holding capacity and biota are significant concerns worldwide. Pimentel et al. (1995) estimated the total on- and off-site costs of erosion to be over $44 million. They estimated a benefit/cost ratio of 5.24 for applying soil conservation practices, including surface residue management. Additionally, recent National Resource Inventory (USDA, 1997) results showed that US erosion control efforts have begun to slow (Figure 2). An expert panel report from the Soil and Water Conservation Society highlighted increased erosion risk associated with climate change, in particular more frequent and intense storm events (SWCS, 2003). These figures highlight the importance of erosion prevention; it is imperative that residue removal be considered only when soil conservation will not suffer as a result.

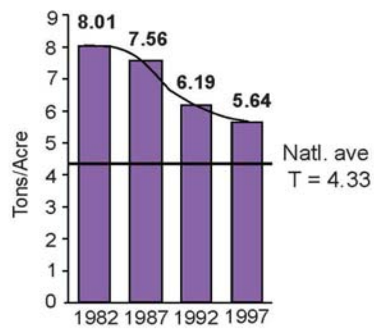
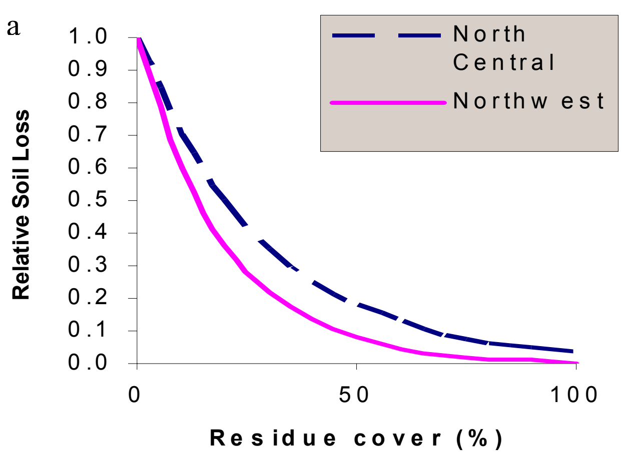


Figure 2. National annual soil loss (USDA-NRCS SQI, 2003)

Conversely, in some regions the combination of crop, management practice, soil and climate work together to produce more than is needed to maintain soil tilth. In some cases, so much is produced that it is deleterious to future crop growth. Here, excess residues could potentially be used for conversion to biomass energy. However, for other cropping, soil, and climate combinations (especially in arid regions), residue production is inadequate even for basic soil protection (Parr and Papendick, 1978) (Figure 3). It is important to discern what combinations make harvest possible, or even beneficial, and at what rates.



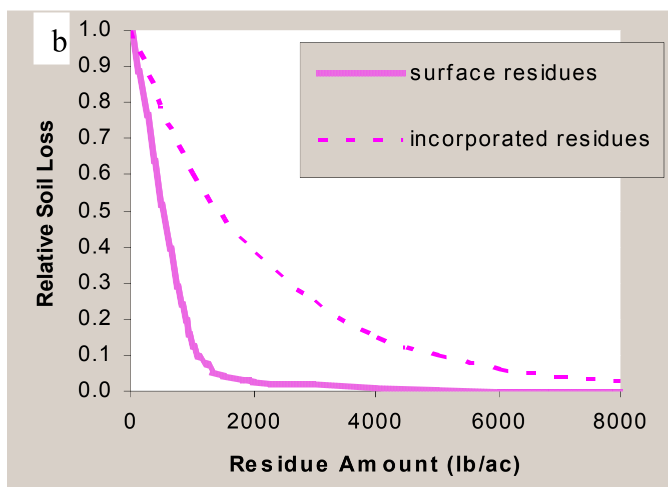


Figure 3. Differences in residue effectiveness for erosion control with climate and management practice: a) the relationship between soil residue cover and relative soil loss in two regions, showing soil protection to be greater in the Northwest region; and b) differences in protection when residues are incorporated into soil (with tillage) versus left on the surface for the Northwest, showing much great soil loss expected when residues are incorporated. Relative soil loss was determined as the ratio of soil loss for a particular amount of cover divided by the soil loss with no cover (McCool et al., 1995).

Many studies of residue removal effects on erosion use simulation models. Lindstrom et al. (1979; 1981) used USLE to estimate potential soil loss for different tillage and crop rotations in the Corn Belt. They suggested that greater than 1.3 x 10^6 MG of stover could be removed from more than half of the farmed acreage without adverse effect. However, this result included harvest from low residue crops and assumed erosion to T is sustainable. Using USLE, these studies predicted that, in general, removal rate had a greater effect on soil loss than tillage, with soil loss highest in conventional tillage with high residue removal and lowest under no till with low residue removal (Lindstrom et al., 1979). In contrast, in a field study Lindstrom et al. (1984) reported the highest runoff under no-till compared with conventional and conservation tillage. (Length of time in no-till was not mentioned.) They found that surface residue increased the amount of rainfall energy (or duration of rainfall event) needed to initiate runoff but had no effect when infiltration was already impaired, such as within wheel tracks.

Lindstrom (1986) found increased runoff and soil loss with decreasing residue remaining on the soil surface under no-till. Study results suggested that a 30% removal rate would not significantly increase soil loss in this system (Figure 4). In a long term residue and tillage management study, residue removal (at various rates) doubled erosion regardless of tillage history. Soil tillage following residue removal increased soil loss between 26% and 47% (Dabney et al. 2004). In a related study, Wilson et al. (2004) reported runoff occurred sooner under the no till than under the tilled treatments due to the temporally increased permeability of freshly tilled soil. However, the relationship between sediment concentration and runoff rate for the tilled system was considerably more sensitive to residue cover than for the no-till system, and the relationship became weaker as residue cover increased. Wilson et al. (2004) concluded, therefore, maintenance of residue cover was more important in the tilled system, particularly on land with a history of CT.

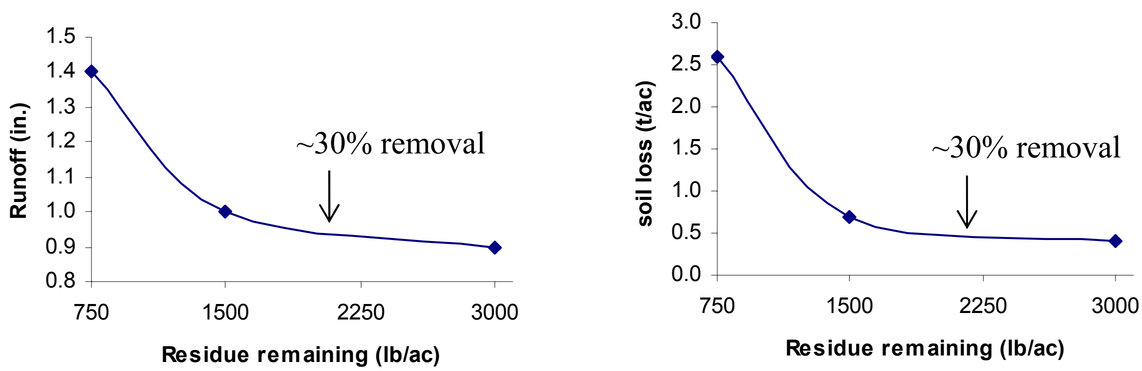


Figure 4. Actual runoff and soil loss reported for three levels of residue remaining in no-till corn plots in Minnesota, showing a tapering off effect of residues' protection of soils at levels approximately equivalent to 30% removal (after Lindstrom, 1986).

In a review of numerous field studies, Benoit and Lindstrom (1987) reported that no-till without residue can often allow more soil erosion than conventional tillage, but no-till with residue cover usually results in less soil erosion than conventional tillage, highlighting the importance of tillage-residue interaction when assessing the effects of residues on soils. Due to soil-specific differences in random roughness and consolidation in response to tillage, Benoit and Lindstrom (1987) suggested that soil taxonomy be used as a guide to tillage-removal recommendations.

Nelson (2002) estimated the amount of corn and wheat straw residue available for harvest from all land capability class I-IV soils in 37 Eastern and Midwestern states by county. To accomplish this, the crop yield required at the time of harvest to insure that T is not exceeded was estimated for each county utilizing RUSLE or WEQ, depending on whether wind erosion or water erosion posed the greatest risk of soil loss, using NRCS databases. RUSLE or WEQ was run using measured yield averages for each county to obtain estimates of actual residue production for a three-year period. Nelson reasoned that subtracting the predicted amount of residue required, such that T (calculated from the first set of analyses) would not be exceeded from the amount of residue calculated from actual yield data would result in the amount of residue available for harvest. He concluded that approximately 43 million metric tons of corn stover (primarily in NE, IA, IL, IN and KS) and more than 8 million metric tons of wheat straw (in KS, TX, OH, IL and MO) was available for removable each year, from 1995-1997 (Nelson, 2002).

Nelson's (2002) work is an excellent first step toward recommending residue removal rates. Some future hurdles include predicting the sources of the large annual variations (e.g., climate is cited by Nelson as one reason), extending results to all regions and soils, and extending the prediction to include more than just soil loss as a resource concern. To fully consider the soil quality impacts of residue removal, this method needs to be extended to include effect on soil C, nutrients, biota, and future crop yield (preferably packaged into an easy-to-use decision tool). Unfortunately, the first attempts to extend this work to soil C do not include feedback loops between erosion and soil carbon pools (Sheehan et al., 2002) and, therefore, overestimate SOC levels. As available models improve, this next step will become easier to accomplish.

♦ **Soil Organic Matter**

In a recent study, Clapp et al. (2000) attempted to tease apart the roles of residue, tillage and N fertilization in soil organic matter accrual by determining the source of C in the organic matter over a period of 13 years. All three management factors affected SOC storage (or carbon sequestration). Corn-derived SOC was greatest under no-till without residue removal but lowest in no-till when stover was removed. Conventional and reduce tillage treatments were intermediate regardless of whether residues were harvested or returned.

Clapp et al. (2000) also found that N fertilization was required to increase SOC storage when stover was left in the field for no-till. Likewise, Power and Doran (1988) found that in the absence of N fertilization in no-till corn, residue decomposition leading to SOC accrual took place by immobilizing soil N, which means less N was available for plant use in the short term.

In one of the few studies to compare residue removal effects under moldboard plowing, Reicosky et al. (2002) found that total C and N remained virtually unchanged over the 30 year study. This is in agreement with the Clapp et al. (2000) study, which found that when the soil was moldboard plowed, residue with additional N fertilization did not increase SOC. Similarly, Dick et al. (1998) concluded that tillage and rotation had greater effects on C accrual than did residue removal.

Gale and Cambardella (2000) found that root derived carbon inputs were greater than residue contributions for oats grown under simulated no-till. This result also calls into question the importance of residues for maintaining SOC. Tillage may also have a stronger effect than residues for SOC accrual. However, even if residues do not contribute significantly to SOC accrual, their presence on the soil surface reduces erosion losses of organic matter.

In a review of residue effects, Reicosky et al. (1995) reported a strong relationship between residue amount and organic matter in the soil's top 15 mm in the US southern piedmont region. They further state that residue production and organic matter is largely controlled by crop choice, tillage, fertilization and climate. Supporting this claim, Potter et al. (1998), in a study of tillage and residue removal systems across Texas, found that no-till without residue removal in cooler, drier climates (within the rainfall limit for continuous cropping) was more effective in sequestering SOC than the same system in warmer and humid areas.

♦ Nutrients

Residue harvest removes more nutrients from the agroecosystem than grain harvest alone. In a study predicting nutrient loss by region from both residue removal and losses resulting from expected erosion increases with reduced soil cover, the greatest loss was predicted for the U.S. Midwest (Holt, 1979). Lindstrom (1986) reported net losses of nutrients for high removal rates in no-till corn, suggesting that increased fertilization rates will be needed to maintain soil fertility.

Conversely, Power and Doran (1988) found that increasing residue return rates, increased total N uptake (immobilization) from soil, suggesting that added N fertilizer was needed when residues remain to avoid soil mining for residue decomposition. Similarly, in an experiment in India (in a warm and humid climate and soils with very low organic matter), Beri et al. (1995) compared residue removal, burning, and incorporation for rice and wheat on tilled soils. The incorporated residue treatment had the highest soil mineral N and P but the lowest yields for both crops. The authors attributed this result to immobilization of N and P during microbial decomposition of the incorporated residues, making the nutrients unavailable to support plant growth. Clapp et al. (2000) had similar results in no-till corn, noting that added fertilizer N increased residue-derived carbon sequestration.

Grande et al. (2005) found that crop residues had no effect on concentrations of total phosphorus (TP) and dissolved reactive phosphorus (DRP) in runoff. However, runoff loads of TP and DRP for residue amended soil were significantly lower compared with treatments with residues removed, due to reduced amount of runoff under residue. In this instance, residues helped to conserve water quality.

♦ Other Indicators of Soil Quality

Karlen et al. (1994) found that 10 years of residue removal under no-till continuous corn, resulted in deleterious changes in many biological indicators of soil quality including lower soil carbon, microbial activity, fungal biomass and earthworm populations compared with normal or double rates of residue return. Reduction in these properties and populations suggests loss of soil function, particularly reduced nutrient cycling, physical stability, and biodiversity. In addition, some disease-producing organisms are enhanced by residue removal, others by residue retention. Residue effect on pests and disease would depend on cropping practice, climate, and local pest or disease incidence.

Stover return has also been shown to make positive changes in physical indicators of soil quality. For instance, Clapp et al. (2000) found reduced bulk density in tillage treatments that included crop residues. Conversely, Dam et al., 2005 found no changes in soil bulk density associated with corn residues. Karlen et al. (1994) also reported greater aggregate stability in soils receiving residues than those with residues removed. Due to the relationship of residues to improved aeration and microbial biomass, Molina-Barahona et al. (2004) used crop residues as a biostimulant for natural remediation of diesel fuel removal in soil.

♦ Yield

In the Southeastern coastal plain, Karlen et al. (1984) compared various removal rates in no-till and conventional tillage with incorporated residues. They found that harvesting crop residues increased macronutrient removal, decreased soil cover, but had a varied effect on corn grain yield. There were no differences between treatments when yields were averaged over three-years. They concluded that some residue could safely be harvested for biofuel production, provided that residue nutrients were replaced by additional fertilization (Karlen et al., 1984).

Power et al. (1986) found increased crop yields for corn and soybean when residues were left on the soil surface compared with yields under residue removal in Nebraska. This yield effect was most pronounced in drier years, leading them to attribute yield increases to residue-induced water conservation. They also cited benefits from reduced erosion and increased soil organic matter. Likewise, in a sister report to Clapp et al. (2000), Linden et al. (2000) found that corn yields in residue-returned treatments exceeded those of corn with no residue by approximately 22% in drier than average years. Differences were not significant in years with near average precipitation. However, this effect was tillage dependent: residue-induced differences in yield were most apparent in the reduce tillage (chisel plow) treatments and not significant in the no-till plots, which began to show yield declines after year four regardless of residue.

Other studies of residues have reported reduced yields due to lower soil temperatures that result in poor germination and delayed silking (Swan et al., 1987). Dam et al. (2005) also reported poorer emergence under no till corn with residues intact compared with residues removed and conventional till with and without residues, which they attributed to cooler soil temperatures and higher soil moisture. However, Dam et al. (2005) found no differences in grain yields or dry matter yields over the 11 year study on sandy loam soils.

Residue age and placement affects soil moisture and temperature. Sauer et al. (1996) found that fresh residue, being thicker, provided more insulation and, therefore, reduced evaporation and temperature compared with strip and weathered residue and bare soil. Soil temperatures are lower under residues due to surface reflectance. The extent of this effect varies with color, water content (Benoit and Lindstrom, 1987) and thickness of the residue layer, all of which change with age or weathering or residue (Sauer et al, 1996).

Some Midwestern studies reported lower yields in conservation tillage associated with large amounts of residue on poorly drained, fine–textured soils (Benoit and Lindstrom, 1987). Since these soils often have low erosion risk, residues might safely be removed, eliminating residue-related slow germination and adding value as biofuel harvest. Sharratt et al. (1998) found that stubble mulch under no-till had higher winter soil temperatures and earlier spring thawing when compared with residue removal or chopping. Therefore, retained corn stover residue should be left upright in the field in colder climates to avoid problems with spring seed germination due to low soil temperatures yet maintain residues' soil protective properties where needed.

While short-term yield effects of residue removal, such as the soil moisture and temperature effects described above, are well-studied, long-term effects are less numerous. However, if residue removal does results in increased erosion, reduced SOM and nutrient levels, and lower biotic activity, yield is very likely to be suppressed as well. Other potential economic trade-offs to residue removal, include higher fertilizer costs and higher fuel costs with more field passes. In addition, reduced soil quality and SOM may preclude participation in carbon trading markets and in some USDA conservation programs, such as Conservation Security Program, which uses SOM trend as a gatekeeper for participation. Both short and long-term effects should be weighed when making a determination about residue removal.

Recommendations

The existing research trends can be used to guide practices to some extent, especially for corn stover harvest in the Corn Belt. In addition, the recent reviews and evaluations of the economics and energetics of biofuels help put the costs and benefits into perspective (Table 3). To move these beyond general recommendations, however, site-specific guidelines for residue harvest need to be developed.

Table 3. Potential Effects of Corn Stover Harvest

Factor	Benefits of Removal	Reference	Costs of Removal	Reference
Economic	Stover sale revenues (~$35/ton); Greater seed germination in colder climates	Glassner et al., 1999; Linden et al., 2000	Yield decreases in dry years due to lower soil moisture; Yield decreases with increased soil loss; Poorer germination but no yield effect	Clapp et al., 2000; Power et al., 1986 Pimentel et al., 1995; Lindstrom, 1986; Dam et al., 2005
Fossil fuel use	Increased EtOH production	Glassner et al., 1999	More field passes required; Fossil fuel needed for conversion to biofuel	Wilhelm et al., 2004; Ulgiati, 2001
Micro-climate	Warmer spring temperatures	Mann et al., 2002	Increased evaporation, lower soil moisture	Sauer et al., 1996
Pests and disease	Increased control for some	Mann et al., 2002; Forcella et al., 1994	Decreased control of others	Mann et al., 2002
Carbon & nutrients	Decreased but moderated by tillage and N rate	Clapp et al., 2000	Nutrient loss predicted greatest in Midwest	Holt, 1979
Erosion	Moderated by amount of harvest and tillage type	Benoit and Lindstrom, 1987	Increased soil loss and water runoff	Lindstrom, 1986

- ✓ **Residue Removal Rates.** Sustainable residue removal rates for biofuel production will vary by system, according to such factors as management practice, crop yield, climate, topography, soil type and existing soil quality. Keeping in mind that gravimetric rates are not the same as percent soil cover, appropriate conversion is necessary and will vary by crop and region. While areas with low slopes and high yields may support some residue harvest, in many areas the residue amounts required for maintaining soil quality will be higher than current soil cover practices. Removal rates will need to be reduced as climates become warmer or more humid, for lower C:N residue or lower yielding crops, as soil disturbance (e.g. tillage) increases, or as soils become coarser textured, compared to the conditions in which most studies occurred (in the U.S. Midwest Corn Belt for no-till corn). Therefore, a decision tool might include inputs of climate (user county or zip code), expected yield and other biomass inputs (such as cover crops or manure), crop (if considering alternatives to corn), slope, soil texture and tillage regime. Tools like RUSLE2, WEQ, and the Soil Conditioning Index (SCI) are likely to be the most practical ways to predict safe removal rates. An expert system with the above inputs could be developed based on model runs of RUSLE2 and SCI. To be accurate, predictive tools must ensure proper feedbacks (credits and debits) for soil changes. However, any guidelines based on models should be validated by field observations. This is especially true of the SCI because it is largely a qualitative tool.

- ✓ **Additional Conservation Practices.** Other conservation practices such as contour cropping or conservation tillage must be used to compensate for the loss of erosion protection and SOM seen with residue removal (Larson, 1979; Lindstrom et al., 1981). In many regions, cover crops are a viable alternative. Green biomass, as with a cover crop, is considered to be 2.5 times more effective than crop residue in reducing wind erosion (in predictive models), especially if the residue is laying flat (McMaster and Wilhelm, 1997).

- ✓ **Crop Alternatives.** Crop residue biofuels may not be a viable option, energetically or economically, according to several recent reviews of biofuel production. Ulgiati (2001) found that the energy invested to produce the biofuel (including crop production, conversion technology, transport, etc.) was not sufficiently greater than the quantity and quality of energy produced to make the process feasible on a large scale, particularly when environmental costs are considered (Giampietro et al., 1997). Another more viable option may be crops grown specifically as energy crops, including herbaceous energy crops like switchgrass and short-rotation woody crops like hybrid poplar (as mentioned in President Bush's (2006) State of the Union Address). Being perennials, these crops require few field passes and little soil disturbance, resulting in low erosion rates. Paine et al. (1996) recommended growing these crops on marginal lands, such as highly erodible land (HEL), poorly drained soils or areas used for wastewater reclamation, which would avoid competition with food crops and increase the amount of arable land. A large amount of land in the Corn Belt is classified as HEL (Wilhelm et al., 2004) (Figure 5), presumably making this land unsuitable for residue removal but potentially viable for dedicated energy crop production.

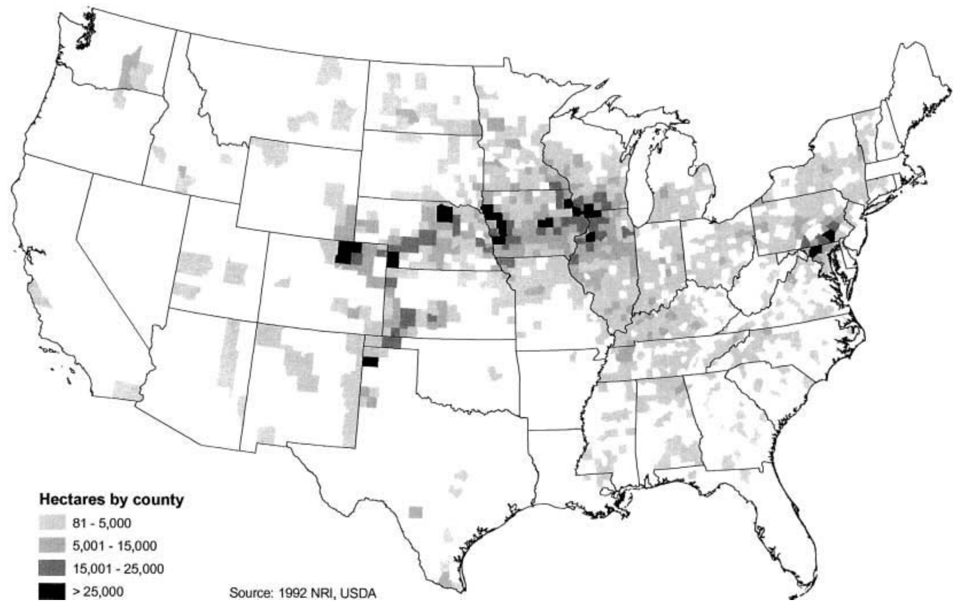


Figure 5. US Highly Erodible Cropland (USDA, 1995)

- ✓ **Periodic Monitoring and Assessment**. Regardless of the specific residue removal practice chosen, fields should be carefully monitored for visual signs of erosion or crusting. Periodic checks of SOC as part of a fertility testing regime are also recommended. Removal rates should be adjusted in response to adverse changes: if erosion increases or SOC decreases, removal rates must be reduced to maintain soil quality.

Because crop residues perform important ecosystem services, their sustainable use will only be accomplished through the use of site-specific harvest rates. New technologies for one-pass harvest must include within field variable harvesting rates so that guidelines can be applied. Additional conservation practices to control erosion and add soil organic matter will help alleviate negative effects of harvest. Adaptive management practices that include monitoring and assessment will be necessary as new technologies and practices are used. In the long term, dedicated energy crops are likely to be the most viable option. Guidelines, developed or endorsed by USDA, that outline these measures will help to ensure that soil quality is not sacrificed in the name of renewable biomass energy.

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