PRECISION CONSERVATION: SITE-SPECIFIC TRADE-OFFS OF HARVESTING WHEAT RESIDUES FOR BIOFUEL FEEDSTOCKS

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ABSTRACT

Crop residues are considered to be an important lignocellulosic feedstock for future biofuel production. Harvesting crop residues, however, could lead to serious soil degradation and loss of productivity. Our objective was to evaluate trade-offs associated with harvesting residues including impacts on soil quality, soil organic C and nutrient removal. We used cropping systems data collected at 369 geo-referenced points on the 37-ha Washington State University Cook Agronomy Farm to aid our evaluation. Site-specific field estimates of lignocellulosic ethanol production from winter wheat residues ranged from 813 to 1767 L/ha and averaged 1356 L/ha suggesting that targeted harvesting of crop residues may be an important consideration. Harvesting winter wheat residues reduced remaining residue C inputs to levels below that required to maintain soil organic C under conventional tillage practices. This occurred as a function of both residue removal and the inclusion of a low residue producing spring pea crop in rotation with wheat. Harvesting winter wheat residues under conventional tillage resulted in negative Soil Conditioning Indices (SCI) throughout the field. In contrast, SCI's under no-till were positive despite residue harvesting. Estimated value of nutrients (N, P, K, S) removed in harvested wheat residue was $13.71/metric ton. In high residue producing areas of the field, the estimated value of harvested residue in fertilizer replacement dollars was over $25/ha. We concluded that substantial trade-offs exist in harvesting wheat straw for biofuel, that trade-offs should be evaluated on a site-specific basis, and that support practices such as crop rotation, reduced tillage and site-specific nutrient management need to be considered if residue harvest is to be a sustainable option.

Keywords: wheat residue, biofuels, precision conservation

INTRODUCTION

Harvesting crop residues for bioenergy production is an opportunity to augment the utility of cereal crops. Currently, corn stover is 41% and wheat residues 15% of the 550.4 million dry tons of crop residues produced annually in the U.S. (Perlack et al., 2005). Although converting lignocellulosic feedstocks to ethanol is an active area of research and development, expectations are that 60 to 80 gallons of ethanol could be produced per dry ton of residue (Sarath et al., 2008). But as crop residues serve vital agricultural functions, caution must be used in considering residue removal so as not to compromise ecosystem services or undermine soil productivity (Nelson et al., 2004; Lemus, R., and R. Lal. 2005; Johnson et al., 2006; Graham et al., 2007; Wilhelm et al., 2007; Lal, 2008; Blanco-Canqui and Lal, 2009). It can be argued that crop residue returns to soil are already insufficient as soil erosion and organic matter depletion are symptomatic of many production systems (Mann et al., 2002; Montgomery, 2007).

Concepts of precision conservation and agroecology recognize the importance of evaluating trade-offs associated with multifunctional landscapes. As agricultural expectations broaden to include food, feed, energy and agroecosystem services and as technologies and decisions become more site-specific, the importance of evaluating site-specific trade-offs increases. Our overall objective is to determine trade-offs associated with harvesting wheat straw including potential ethanol production, changes in soil quality and nutrient removal on a site-specific basis that takes into account related production factors such as tillage and crop rotation. Although not comprehensive, this evaluation provides first steps towards quantifying key considerations that should help inform agricultural decisions.

SITE-SPECIFIC FIELD EVALUATIONS

The study was conducted on a 37-ha field at the Washington State University Cook Agronomy Farm (46° 47' N, 117° 5' W) located five km NE of Pullman, WA. The field has terrain and silt loam soils that developed in loessial deposits with complexes of the Palouse (Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls)-Thatuna (Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls)-Naff (Fine-silty, mixed, superactive, mesic Typic Argixerolls) association (USDA Soil Survey of Whitman County, WA, 1980). A systematic, non-aligned grid of 369 geo-referenced sampling locations was established in 1999 representing an average density of 10 samples per ha. In 1999 and 2000 spring wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.), respectively, were grown over the entire field. Grain yield was hand harvested on 2 m^2 areas at each of the 369 geo-referenced locations and aboveground biomass (both crop yield and residue) on 1/3 of the locations. Samples were threshed to separate grain from straw, dried and weighed to express grain and straw biomass on an area basis. In 2001, three year crop rotations were imposed as field strips with each crop represented every year. The crop rotations consisted of winter wheat-X-spring wheat where X represented an alternative rotation crop of winter and spring cultivars of barley, pea (*Pisum arvense* L.) and canola (*Brassica napus annua* Koch). From 2001 through 2003 crop yields and aboveground residue were harvested as described at each geo-referenced point and relative yields for a given location averaged across the five year (1999-2003) time period. Relative yield data were interpolated using ordinary kriging (GSLIB, Deutsch and Journel, 1998) to display field spatial patterns (Fig. 1).

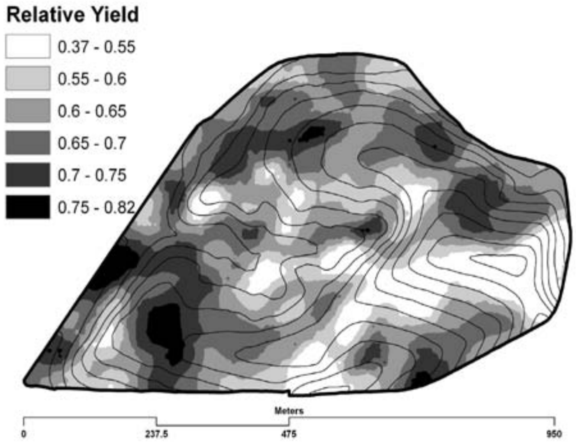

Figure 1. Spatial distribution of the relative yield of all crops grown on a 37-ha field from 1999 through 2003 including wheat, barley, pea and canola.

The relative yield map and associated harvest indices were used to distribute field yield and residue variability for a simulated winter wheat-spring pea-spring wheat rotation where average whole-field yields typical for the area were used: winter wheat, 6480 kg/ha, spring pea, 2240 kg/ha and spring wheat, 4370 kg/ha. These site-specific yield and harvest index estimates were then used as input for calculating winter wheat residues that could be harvested as biofuel feedstocks, estimating residue C and nutrient (N, P_2O_5, K_2O and S) removal and for assessing USDA NRCS Soil Conditioning Indices (SCI; USDA, 2006). For calculating the site-specific potential for biofuel production from harvested residues, we assumed a 50% residue harvest efficiency (Perlack et al., 2005) and a lignocellulosic ethanol conversion of 77 gallons of ethanol/dry ton of winter wheat residue (Kadam and McMillan, 2003). We also assumed that crop residue harvest would only occur for winter wheat (once every three years) and not after the production of spring pea or spring wheat that have relatively low residue yields. To calculate the SCI, estimates of site-specific crop yields were combined with the field operations disturbance ratings and Revised Universal Soil Loss Equation (RUSLE) calculations for each of the 369 geo-referenced points. We estimated soil erosion for two different scenarios, a conventional, moldboard plow based tillage system and a continuous no-tillage system under the same three-year rotation described. For RUSLE, we used R_{eq}, LS, P and C factors for the field based on McCool et al., (1989); McCool, (1992); Desmet and Glovers, (1996); and Renard et al., (1997); while K factors were based on published values of soil series. Field operation disturbance ratings required for SCI calculations were based on field operations typical for the two different tillage regimes throughout the three year rotation.

Estimated Ethanol Yields

Estimated ethanol yields from harvesting winter wheat straw for the 37-ha field varied over two-fold ranging from 813 to 1767 L/ha and averaging 1356 L/ha (Fig. 2). Assuming a retail price of $0.53 per L for ethanol, the retail value of ethanol derived from this field would be $719 per ha. Due to the range in production, however, some portions of the field would likely be more economical to harvest than others. Therefore, site-specific data on crop residue yields would likely be valuable (Long et al., 2010). These estimates of ethanol yield from winter wheat straw would only occur once every three years in a three year rotation. However, if returns were attractive to producers, there would likely be an intensification of winter wheat in the crop rotation leading to shorter rotations. If this were to occur, it is also likely that tillage and potential negative effects of residue removal would increase, as no-till systems are more reliant on crop rotation to manage disease and weeds (Huggins and Reganold, 2008).

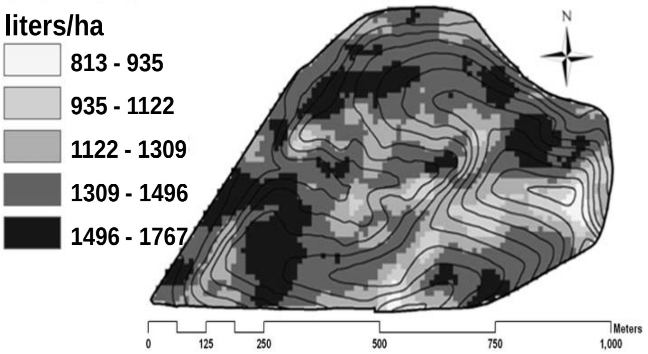

Figure 2. Potential ethanol production (L/ha) from harvesting winter wheat residues at site-specific field locations at the WSU Cook Agronomy Farm.

Crop Residue Carbon Inputs

The biomass C of winter wheat crop residues estimated from sampled harvest indices and total C analyses (dry combustion, Leco C/N/S analyzer) ranged from 2048 kg C/ha to 4455 kg C/ha and averaged 3428 kg C/ha for the field (Fig. 3). Field averages for spring pea and spring wheat crop residues averaged 980 kg C/ha and 2343 kg C/ha, respectively. Annual returns of C required to maintain soil organic C (SOC) levels in higher producing areas of the dryland wheat producing areas of the Pacific Northwest have been estimated as 2000 to 2500 kg C/ha (Rasmussen and Collins, 1991). If the C in harvested winter wheat straw is subtracted from the total produced, the remaining winter wheat residue C inputs are less than 2000 kg C/ha at nearly all field locations (Fig. 4). Therefore, the residue C returned to soil the year following winter wheat residue harvest can be considered marginal at best for maintaining SOC. Crop rotation is also an important factor as residue C inputs need to be calculated on an annual basis to determine if sufficient to maintain SOC. In this case, spring pea residue C returns are less than ½ that required while average spring wheat residue

C inputs are just sufficient. Consequently, over the three year crop rotation, winter wheat residue C inputs would have to compensate for low spring pea residue C and any residue harvest would likely result in SOC declines over time. The estimates of residue C inputs required, however, were made for conventional cropping systems with inversion tillage. As residue C inputs to maintain SOC are likely less under no-till than conventional tillage, conversion to no-till may enable more sustainable residue harvesting. To explore this situation, we calculated the site-specific SCI when winter wheat is harvested under two different tillage regimes.

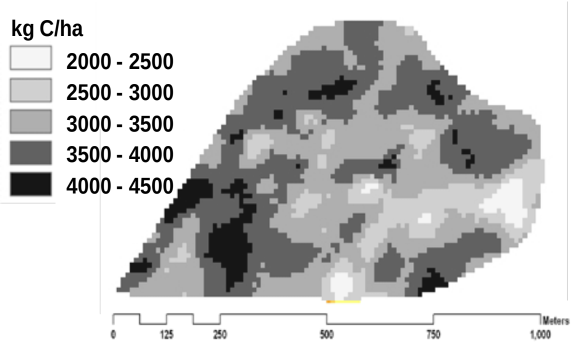

Figure 3. Estimated amounts of pre-harvest winter wheat residue C (kg C/ha) at site-specific field locations at the WSU Cook Agronomy Farm.

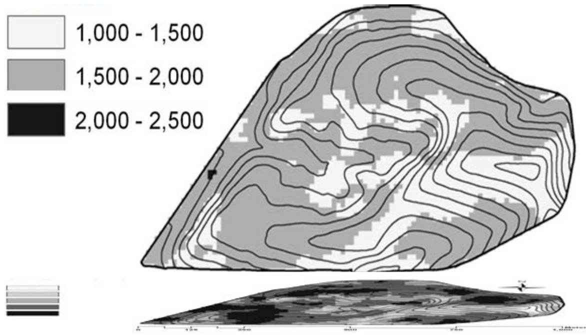

Figure 4. Estimated remaining winter wheat residue C (kg C/ha) after harvesting (baling and removal) at site-specific field locations at the WSU Cook Agronomy Farm.

Soil Conditioning Index

Estimated SCI under conventional tillage ranged from -0.96 to +0.07 when wheat residues were harvested (Fig. 5). Negative SCI values indicate that soil quality is declining due to soil erosion and lack of sufficient C inputs. The most negative SCI’s occurred on steeper field slopes. Shifting from conventional tillage to no-till resulted in nearly all field locations exhibiting a positive SCI (Fig. 6). These positive values of SCI indicate that harvesting winter wheat residues under no-tillage may be a sustainable option with respect to soil quality. Banowetz et al. (2008) also used the USDA-NRCS Soil Conditioning Index to calculate the amount of straw from grass and wheat required to maintain soil quality. They reported that 1.03 Mt of straw were available from a total of 2.24 Mt produced in the Pacific Northwest states of Idaho, Washington, and Oregon.

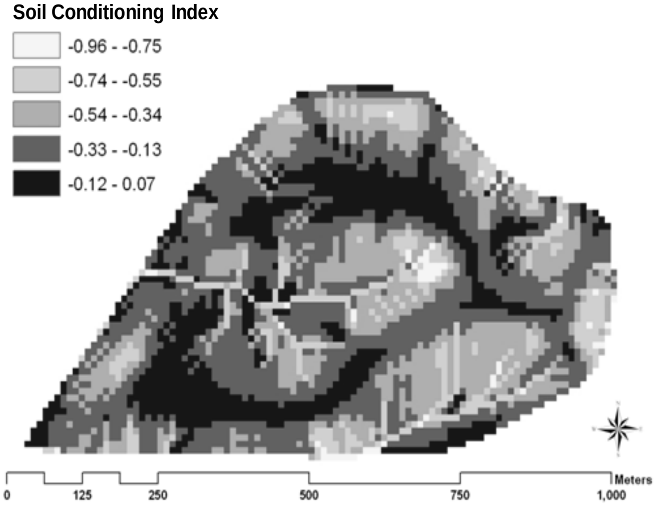

Figure 5. Estimated Soil Conditioning Index (SCI) under a three year winter wheat-spring pea-spring wheat rotation using conventional tillage (moldboard plow based).

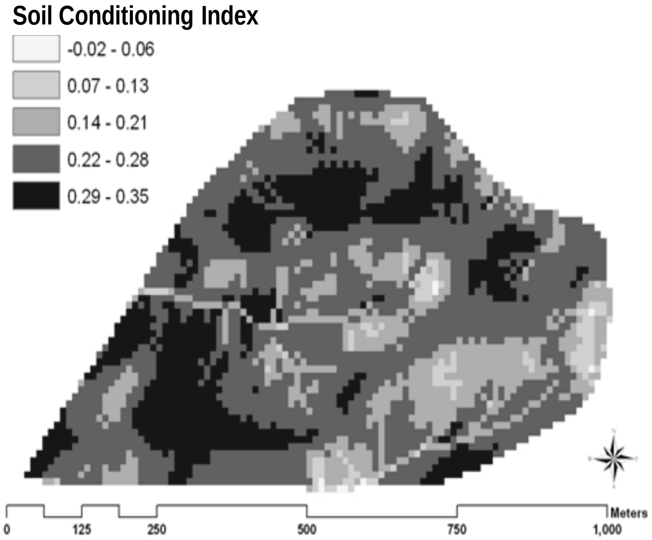

Figure 6. Estimated Soil Conditioning Index (SCI) under a three year winter wheat-spring pea-spring wheat rotation using continuous no-tillage.

Nutrient Removal

Harvesting residues will also result in removal of essential crop nutrients that will eventually need to be replaced, often with additional applications of synthetic fertilizers. Using concentrations of major nutrients typically found in wheat straw (nitrogen: 0.4%; phosphorus, expressed as P_2O_5: 0 .15%; potassium, expressed as K_2O: 1%; and sulfur: 0.08%), field variations of nutrient export in harvested winter wheat residues were calculated (Fig. 7). These estimates demonstrate that the export of nutrients in harvested straw represents a significant cost to producers if not recaptured in the sale of the residue. In addition, the export of bases in wheat residue will result in the acceleration of soil acidification, a growing problem in the higher producing dryland wheat areas of the PNW (Brown et al., 2007). Considering fertilizer prices of \$0.23/kg N, \$0.27/kg P_2O_5, \$0.14/kg K_2O, and \$0.18/kg S, each metric ton of dry residue would contain nutrients valued at \$13.71/metric ton. Considering high residue producing areas of the field, the value of harvested residue in fertilizer replacement dollars would be over \$25/ha (Fig. 7 combined with given fertilizer costs). Certainly, the value of harvested wheat residue in terms of fertilizer replacement dollars needs to be considered by producers as well as site-specific nutrient management if soil nutrient levels are to be maintained.

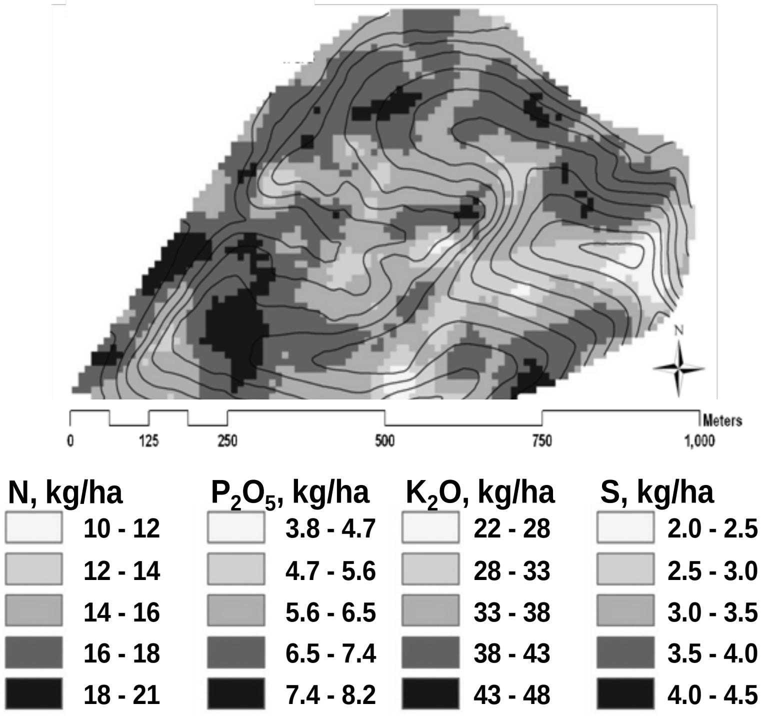

Figure 7. Estimated export of nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), and sulfur (S) in harvested winter wheat straw.

SUMMARY AND CONCLUSIONS

Field variability in wheat residues resulted in a two to three fold range in estimated biofuel production capacity from a site-specific standpoint. This range in residue production may be an important consideration and lead to site-specific harvesting strategies. Crop rotation is also an important consideration as it influences available residue quantities in any given year as well as annual returns of C required to maintain soil organic matter. Crop residue C returns must be evaluated on a rotation basis, not just the crop from which residues were harvested. Trade-offs to harvesting wheat residues include potential degradation of soil (e.g. increased soil erosion, loss of soil organic matter) and nutrients exported in straw. Coupling residue harvesting with conservation tillage may be essential to minimize adverse soil degradation effects. These trade-offs also varied considerably throughout the field and would also be amenable to site-specific management practices such as precision nutrient management. Other important trade-offs that were not evaluated include improved plant-available water and drought resistance as well as wildlife habitat that are derived from maintaining surface residues. Overall, implementation of harvesting wheat residues for biofuel should carefully consider the site-specific nature of trade-offs and tailor management practices to address site-specific conditions.

REFERENCES

Banowetz, G.M., A. Boateng, J.H. Steiner, S.M. Griffith, V. Sethi, and H. el Nasharr. 2008. Assessment of straw biomass feedstock resources in the Pacific Northwest. Biomass and Bioenergy. 32:629-634.

Blanco-Canqui H. and R. Lal. 2009. Crop Residue Removal Impacts on Soil Productivity and Environmental Quality. Critical Reviews in Plant Sciences 28:3, 139-163.

Brown, T. T., R.T. Koenig, D.R. Huggins, J.B. Harsh and R.E. Rossi. 2008. Lime effects on soil acidity, crop yield and aluminum chemistry in inland Pacific Northwest direct-seed cropping systems. Soil Sci. Soc. Am. J. 72:634-640.

Desmet, P.J.J. and G. Glovers, 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. J. Soil and Water Cons. 51(5): 427-433

Deutsch, C.V. and A.G. Journel. 1998. GSLIB Geostatistical Software Library and User's Guide. Second edition. Oxford University Press, New York, NY. 369 pp.

Environmental Systems Research Institute. 2008. ArcGIS version 9.3. Redlands, CA.

Graham, R.L.,R.Nelson, J. Sheehan,R.D. Perlack, and L.L. Wright. 2007. Current and potential U.S. corn stover supplies. Agron. J. 99:1–11.

Huggins, D.R. and J.P. Reganold. 2008. No-till: The Quiet Revolution. Scientific American. July, 2008. pp. 70-77.

Johnson, J., D. Reicosky, R. Allmaras, D. Archer, and W.W. Wilhelm. 2006. A matter of balance: Conservation and renewable energy. J. Soil Water Conserv. 61:120A–125A.

Kadam, K. L. and McMillan, J. D. (2003), *Bioresour. Technol.* **88,** 17–25.

Lal, R., 2008. Soil quality impacts of residue removal for bioethanol production. Soil Till. Res. 102, 233–241.

Lemus, R., and R. Lal. 2005. Bioenergy crops and carbon sequestration. Crit. Rev. Plant Sci. 24:1–21.nt. 31:575–584.

Long, D.S., J.D. McCallum and D.R. Huggins. 2010. On-combine sensing technique for mapping straw yield within wheat fields. This proceedings.

Mann, L., V. Tolbert, and J. Cushman. 2002. Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion: A review. Agric. Ecosyst. Environ. 89:149–166.

McCool, D.K., G.R. Foster, C.K. Mutchler, and L.D. Meyer. 1989. Revised slope length factor for the Universal Soil Loss Equation. Trans. ASAE 32:1571-1576.

McCool, D.K. 1992. Using divided slopes and field strips for managing variable cropland: effectiveness for reducing runoff and soil erosion. p. 67-69. *In* Veseth, R. and B. Miller (eds.), Precision Farming for Profit and Conservation. 10th Inland Northwest Conservation Farming Conference Proceedings, Washington State University, Pullman.

Montgomery, D.R., 2007. Dirt: the erosion of civilizations. University of California Press. Berkeley, CA. 295 p.

Nelson, R.G., M. Walsh, J.J. Sheehan, and R. Graham. 2004. Methodology for estimating removable quantities of agricultural residues for bioenergy and bioproduct use. Appl. Biochem. Biotechnol. 113:13–26.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply DOE/GO-102005-2135 and ORNL/TM-2005/66.

Rasmussen, P.E., and H.P. Collins. 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semi-arid regions. Adv. Agron. 45:93-134.

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K. & Yoder, D. C. (1997) Predicting Soil Erosion by Water: a Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Handbook 703. US Government Printing Office, Washington DC, USA.

Sarath, G., R.B. Mitchell, S.E. Sattler, D. Funnell, J.F. Pedersen, R.A. Graybosch, and K.P. Vogel. 2008. Opportunities and roadblocks in utilizing forages and small grains for liquid fuels. J. Ind. Microbiol. Biotechnol. 35: 343-354.

USDA Soil Conservation Service. 1980. Soil survey of Whitman county Washington.

USDA, NRCS. 2006. Guide to Using the Soil Conditioning Index.

Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 99:1665-1667.