

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Faculty Publications in the Biological Sciences

Papers in the Biological Sciences

2011

Maize cellulosic biofuels: soil carbon loss can be a hidden cost of residue removal

Amy Kochsiek

Johannes Knops

Follow this and additional works at: <https://digitalcommons.unl.edu/bioscifacpub>



Part of the [Biology Commons](#)

This Article is brought to you for free and open access by the Papers in the Biological Sciences at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Faculty Publications in the Biological Sciences by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.



Maize cellulosic biofuels: soil carbon loss can be a hidden cost of residue removal

AMY E. KOCHSIEK and JOHANNES M. H. KNOPS

School of Biological Sciences, University of Nebraska-Lincoln, 348 Manter Hall, Lincoln, NE 68588, USA

Abstract

Second generation biofuels, like cellulosic ethanol, have potential as important energy sources that can lower fossil fuel carbon emissions without affecting global food commodity prices. Agricultural crop residues, especially maize, have been proposed for use as biofuel, but the net greenhouse warming effect of the gained fossil fuel carbon offset needs to account for any ecosystem carbon losses caused by the large-scale maize residue removal. Using differential ^{13}C isotopic ratios between residue and soil in an incubation experiment, we found that removal of residue increased soil organic matter decomposition by an average of 16%, or 540–800 kg carbon ha^{-1} . Thus, removal of residue for biofuel production can have a hidden carbon cost, reducing potential greenhouse gas benefits. Accurate net carbon accounting of cellulosic biofuel needs to include not only fossil fuel savings from use of the residue, but also any declines in soil carbon caused directly and indirectly by residue removal.

Keywords: biofuels, cellulosic ethanol, priming, residue removal, soil organic matter

Received 23 June 2011 and accepted 22 July 2011

Introduction

Evaluation of the environmental effects of large-scale, indiscriminant residue removal has largely focused on soil erosion and water conservation (Nelson, 2002; Kim & Dale, 2004; Graham *et al.*, 2007) while its potential impacts on carbon cycling has begun to be recognized in the last few years (Blanco-Canqui & Lal, 2007, 2009; Anderson-Teixeira *et al.*, 2009). Clearly, large-scale removal of maize ‘waste’ crop residues for cellulosic ethanol production reduces the quantity of residue-carbon input to the soil organic matter (SOM) carbon pool. Reduced residue input has been shown to change physical patterns of soil structure such as reduction in water infiltration and oxygen status, and changes in temperature regimes (Baumhardt *et al.*, 2004; Blanco-Canqui *et al.*, 2006b, 2007), as well as affecting the stability of soil aggregation patterns (Rhoton *et al.*, 2002; Blanco-Canqui *et al.*, 2006a).

In addition to changing soil physical properties, residue removal can also change the rate of microbial decomposition and potentially lead to a loss of carbon from SOM (Kuzayakov *et al.*, 2000). Some decomposition studies show that addition of plant residue increases SOM decomposition by increasing microbial populations (i.e. ‘priming’), leading to enhanced carbon loss

(Broadbent, 1947; Bingeman *et al.*, 1953; Wu *et al.*, 1993; Cheng *et al.*, 2003). However, other work has suggested the opposite, a decrease in SOM decomposition with simple carbon additions, caused by a shift in microbial substrate utilization toward the easily decomposable residues preferentially over more recalcitrant SOM (Fontaine *et al.*, 2003). Maize residues decompose rapidly, caused by low lignin content combined with high levels of soluble biomass, cellulose and hemicellulose (Kochsiek *et al.*, 2009), which may increase its potential to lead to shifts in microbial substrate utilization. Regardless, the potential of either ‘priming’ or alternatively ‘stabilizing’ effects of residue addition on SOM is an important factor that can enhance or reduce the net global warming benefits of cellulosic biofuel production.

We examined the addition and removal of maize residues (leaves and stalks) on the decomposition of SOM in a laboratory incubation study. We employed differences in the natural abundance of ^{13}C between residue derived carbon and soil derived carbon to partition the release of C via decomposition from both residue and SOM during this 120-day incubation.

Methods

Soil was collected from the High Plains Agricultural Laboratory in Sidney, Nebraska in a site consistently cropped with wheat for over 30 years. The soil type at this site is categorized

Correspondence: Amy E. Kochsiek, tel. +1 402 215 9451, fax +1 402 472 2083, e-mail: akochsiek@huskers.unl.edu

as Pachic Haplustoll with a soil texture of 25% clay, 35% silt and 40% sand (Lyon *et al.*, 1997). Ten random soil samples were taken at 0–10 cm depth in plots that had received tillage. Soil was brought back to the laboratory and stored at 4°C until use.

Maize residue was harvested from Mead, Nebraska in a no-till irrigated continuous maize field at the end of the growing season just before harvest. Residue was separated into leaf and stalk material, dried to a constant mass at 70°C and ground in a Wiley mini-mill with a 40 mesh (2 mm) screen (Thomas Scientific, Swedesboro, NJ, USA). After grinding, leaf and stalk residue was analyzed for total C and N in a Costech 4010 elemental analyzer (Costech Analytical Technologies, Inc., Valencia, CA, USA) and initial carbon quality with the Ankom 200/220 Fiber Analyzer (Ankom Technology, Macedon, NY, USA), which is a common technique used to determine forage digestibility (Goering & Van Soest, 1970; Van Soest *et al.*, 1991). This technique uses a sequential extraction to determine the amount of soluble, hemicellulose, cellulose and lignin fractions within each sample. These classifications do not represent strictly identical chemical compounds, but rather groups of similar compounds with similar resistance to decomposition. The data for tissue fractions analysis are presented as the four fractions (soluble, hemicellulose, cellulose and lignin) totaling 100% of the plant tissue carbon quality. Therefore, any increase in one fraction leads to an equivalent decrease in the other fractions. Maize leaf (C/N~40) and stalk residue (C/N~102) were used because they represent the two largest residue types remaining post-harvest that differ in nitrogen and carbon quality (Table 1) and thereby may potentially influence microbial nitrogen limitation and dynamics.

Soil was homogenized, sieved through a 2 mm mesh, and larger organic fragments such as root and residue were removed by hand. There were three experimental treatments: (1) no residue (soil alone), (2) soil with leaf residue, (3) soil with stalk residue. Residue was ground and 0.28 g was incorporated into 40 g of soil, which is an equivalent ratio of annual produced residue in field maize systems (Verma *et al.*, 2005). We used ground residue to maximize the interaction between residue, soil and microbes, which examines the potential positive or negative effect that residue additions have on SOM decomposition. Each experimental unit was set to a bulk-density of 1 g cm⁻³, 60% water-filled pore space and remained open to the atmosphere during the incubation except during sampling periods to avoid O₂ limitation. CO₂ emissions were sampled (*n* = 6 per treatment) on days 1, 5, 10, 15, 20, 35, 50, 75, 90 and 120. During sampling, experimental units were enclosed in jars, which were then cleared with CO₂ free air.

Twenty-four hours after clearing the jars, headspace was sampled and CO₂ concentration measured on a Shimadzu (Kyoto, Japan) gas chromatograph-17A (version 3) with an electron capture detector and a Porapak Q column. Delta ¹³C of the headspace samples was taken on days 5, 15, 35, 75 and 120 by sampling 12 mL of headspace gas and storing sampled gas in an evacuated exetainer (Labco, Buckinghamshire, UK). Samples were analyzed at the UC Davis Stable Isotope Facility using a SerCon Cryoprep TGII trace gas concentration system interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd, Cheshire, UK). Pee Dee belemnite was used as a standard for δ¹³C measurements where,

$$\delta^{13}\text{C}(\text{‰}) = [({}^{13}\text{C}/{}^{12}\text{C} \text{ sample})/({}^{13}\text{C}/{}^{12}\text{C} \text{ standard})]1000$$

In all treatment combinations, we decomposed C₄ plant material on C₃ soil. Because C₃ and C₄ plants differ in discrimination of ¹³C/¹²C, the soil carbon will have a more negative δ¹³C than the plant material (Table 1). By using the differentiation between the two signatures, we could determine the amount of CO₂ respired carbon that had originated from SOM and from residue decomposition.

Carbon remaining was calculated as the cumulative CO₂-carbon respired over the 120 day experiment minus the initial total carbon in residue and soil. To determine the amount of residue and SOM decomposition, we used a two source mixing model (Rubino *et al.*, 2010) where the contribution of residue to the δ¹³C of the CO₂-C respired was calculated as:

$$\text{CO}_2^{\text{r}}/\text{CO}_2^{\text{t}} = (\delta^{13}\text{CO}_2^{\text{t}} - \delta^{13}\text{CO}_2^{\text{s}})/(\delta^{13}\text{CO}_2^{\text{r}} - \delta^{13}\text{CO}_2^{\text{s}})$$

where CO₂^r/CO₂^t is the fraction of residue derived CO₂ respired over the total CO₂ respired (residue derived + soil derived); δ¹³CO₂^t represents the isotopic composition of sampled air CO₂; δ¹³CO₂^s is the isotopic composition of the CO₂ respired by the control soil; δ¹³CO₂^r is the isotopic composition of residue derived CO₂. The main assumption is that no isotopic fractionation was associated with respiration (δ¹³CO₂^r is the δ¹³C signature of residue and δ¹³CO₂^s is the δ¹³C signature of the soil). We could then calculate the percent of the CO₂-C respired in each sample that originated from SOM decomposition. By multiplying the total CO₂-C respired on each sampling day by the percent of residue and soil respiration determined from the two-source mixing model, we could determine the amount of CO₂-C respired from soil and residue, respectively. We then fit regressions between each sampling date and used these fitted lines to calculate the cumulative amount of CO₂-carbon respired. The differences in the cumulative amounts of CO₂-carbon respired from residue and SOM was analyzed using one-way ANOVA with residue addition as the main effect.

Table 1 Residue quality and δ¹³C of soil and residue additions

	% Soluble	% Hemi-cellulose	% Cellulose	% Lignin	Carbon	Nitrogen	Carbon : nitrogen	δ ¹³ C
Stalk	30.8 ± 1.2	24.3 ± 0.4	38.6 ± 0.9	6.22 ± 0.3	44.1 ± 0.1	0.43 ± 0.03	102.6	-11.8 ± 0.01
Leaf	28.7 ± 0.7	31.0 ± 0.4	33.9 ± 0.7	6.40 ± 0.3	41.9 ± 0.1	1.01 ± 0.42	41.4	-12.8 ± 0.13
Soil	—	—	—	—	2.1 ± 0.02	0.20 ± 0.01	10.5	-22.1 ± 0.63

Shown are the mean ± 1 SE. *n* = 3 for δC means and *n* = 6 for all other quality measurements.

Results

Between days 5–10, rates of $\text{CO}_2\text{-C}$ respired were highest for all treatments than at any other time throughout the incubation period (Fig. 1). All residue addition treatments, regardless of the type of residue addition, were higher than the soil treatments for the first 75 days of the experiment. By 90 days, all treatments were respiring at the same rate. We found that litter addition, regardless of C/N ratio, had a significant increase in total $\text{CO}_2\text{-C}$ respired, but that there were no differences between litter types in this respect.

Residue-C remaining was almost twofold greater for leaves than stalks at the end of the 120 day incubation (One way ANOVA, $F_{1,10} = 77.78$, $P \leq 0.0001$; Fig. 2). We found that the addition of these residues significantly reduced SOM CO_2 respiration by 19% for leaves and 13% for stalks (One way ANOVA, $F_{2,15} = 26.85$, $P \leq 0.0001$) (Fig. 2) when compared with soils that did not receive residue additions.

Discussion

For continuous maize in east-central Nebraska, with residue production averaging $5800 \text{ kg carbon ha}^{-2}$ and a soil carbon pool of $38\,000 \text{ kg ha}^{-2}$ in 0–15 cm depth (Verma *et al.*, 2005), these differences could potentially constitute increased soil carbon loss of as much as $540\text{--}800 \text{ kg ha}^{-1}$ with the complete residue removal. Thus, maize residue removal increases SOM-carbon decomposition under ideal temperature and moisture conditions and therefore, removal of maize residue for biofuel production could have a hidden cost of increased soil carbon loss.

Studies have shown that the presence and quality of residue additions can change decomposer diversity as well as enzyme diversity (Bending *et al.*, 2002; Dilly & Munch, 2004; Dilly *et al.*, 2004; McMahon *et al.*, 2005). While we did not directly measure soil microbial community composition or functioning, this study does show that the application of residue can decrease the amount of soil decomposition in a system. This pattern is likely ecosystem specific and may be more prevalent in maize systems because these systems have large inputs of residue that has very low lignin content. Relatively easy residue to degrade, such as maize, could stimulate a suite of decomposers that create enzymes that specialize in cleaving bonds commonly found in plant residue, which are not as complex or difficult to break as those in SOM (Kuzakov *et al.*, 2000; Fontaine *et al.*, 2003, 2004). Furthermore, because our litter was ground and incorporated into the soil, the small litter particle size most likely enhanced the decomposability of the residue. However, this pattern still warrants

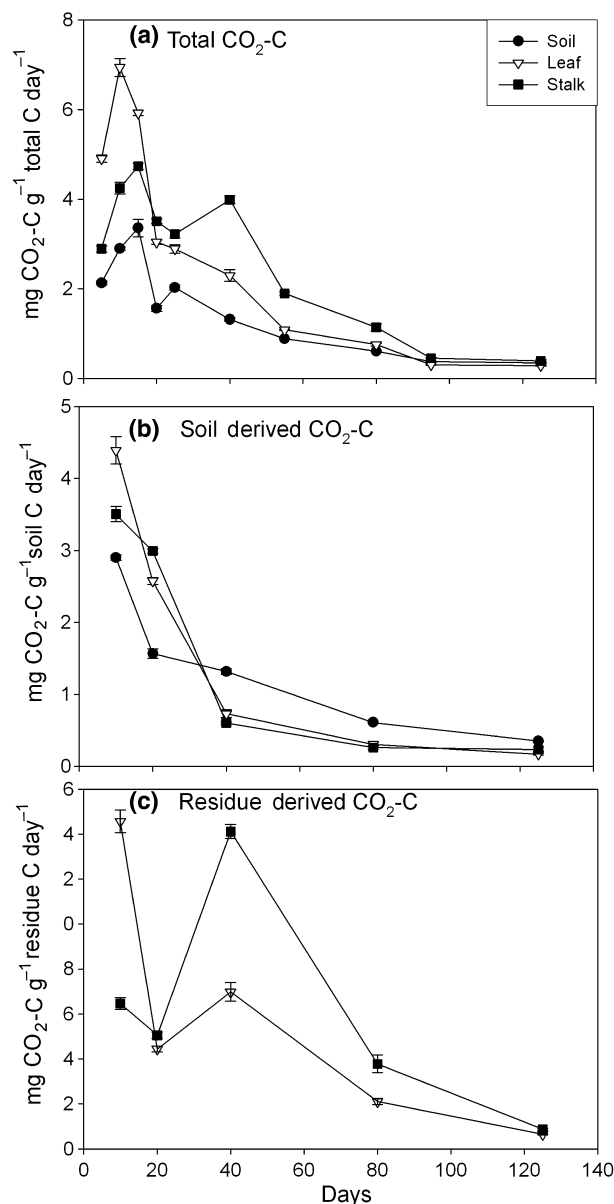


Fig. 1 Rate of $\text{CO}_2\text{-C}$ respired over the 120 day incubation experiment for (a) total (soil + residue) (b) soil and (c) residue at each sampling day. Shown are the mean ± 1 SE. for each treatment at each sampling date ($n = 6$ per treatment at each sampling day).

future work that focuses on identifying shifts in suites of microbial decomposers with substrates of different quality and then measuring both residue and SOM addition to clarify these relationships.

Because SOM-carbon is relatively inert and has a residence time of decades to centuries, this carbon loss can have long-term consequences for ecosystem carbon stocks and offsets part of any reduction in greenhouse gas emissions provided by the use of 'waste' maize

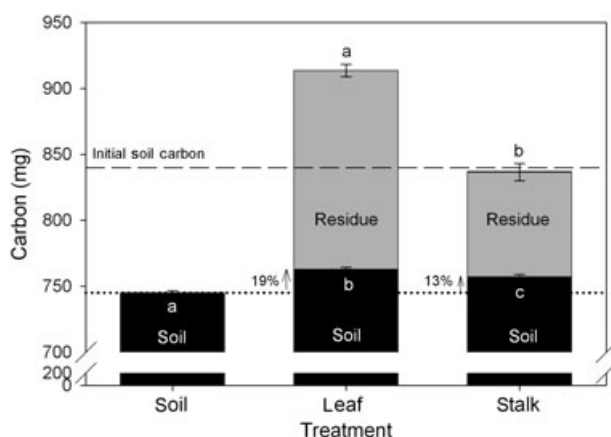


Fig. 2 Carbon change in three treatments, soil only, soil plus maize leaf residue and soil plus maize stalk residue. Stable carbon isotope differences between the soil and residue carbon were used to partition the carbon loss from soil organic matter and residue additions. The dashed line represents the initial soil carbon content in each experimental unit and the stippled line the remaining soil carbon when no residue was added. Soil with no residue added was significantly lower in carbon ($F_{2,15} = 26.85$, $P \leq 0.0001$), indicating that residue removal increases soil organic carbon loss. Shown are the means ± 1 SE.

residues (Blanco-Canqui & Lal, 2007; Anderson-Teixeira *et al.*, 2009). This study demonstrates potential SOM-carbon losses under ideal temperature and water regimes, under more natural conditions, the patterns could be less pronounced and field-based verification is needed. This study focuses on aboveground residue removal, but it should be noted that under field conditions, root biomass would remain and has been shown to contribute more to long-term SOM-C than aboveground biomass in other crop types and ecosystems (Kätterer *et al.*, 2011). However, because maize has relatively less root biomass investment, aboveground residue removal could be more important to SOM-C dynamics in maize based crop systems. The observed increases in SOM-carbon losses, in addition to the direct removal of carbon from the field in residue form, highlights the need for field based soil and residue pool monitoring, which is critical to determine long-term SOM-carbon losses. Incorporating soil carbon changes are essential in life cycle analyses to determine greenhouse gas emission savings when replacing fossil fuels with cellulosic ethanol.

Acknowledgements

This work was supported by grants from DOE-Office of Science (BER: Grant Nos. DE-FG03-00ER62996 and DE-FG02-03ER63639) DOE-EPS-CoR (Grant No. DE-FG02-00ER45827) and the Cooperative State Research, Education, and Extension Service, US Department of Agriculture (Agreement No. 2001-

38700-11092) and the US Department of Education GAANN fellowship. Ramesh Laungani and Clarence Lehman provided comments on this manuscript and Brigid Amos and Cathleen McFadden provided analytical support.

Author contributions

A.E.K. and J.M.H.K designed the field experiment. The incubation and sample analysis was conducted by A.E.K. The manuscript was jointly written by A.E.K. and J.M.H.K.

References

- Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH (2009) Changes in soil organic carbon under biofuel crops. *Global Change Biology. Bioenergy*, **1**, 75–96.
- Baumhardt RL, Unger PW, Dao TH (2004) Soil and crop management – seedbed surface geometry effects on soil crusting and seedling emergence. *Agronomy Journal*, **96**, 1112–1117.
- Bending GD, Turner MK, Jones JE (2002) Interactions between crop residue and soil organic matter quality and the functional diversity of soil microbial communities. *Soil Biology & Biochemistry*, **34**, 1073–1082.
- Bingeman CW, Varner JE, Martin WP (1953) The effect of the addition of organic materials on the decomposition of an organic soil. *Soil Science Society of America Proceedings*, **29**, 692–696.
- Blanco-Canqui H, Lal R (2007) Soil and crop response to harvesting corn residues for biofuel production. *Geoderma*, **141**, 355–362.
- Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. *Critical reviews in plant sciences*, **28**, 139–163.
- Blanco-Canqui H, Izaurrealde RC, Owens LB, Lal R, Post WM (2006a) Rapid changes in soil carbon and structural properties due to stover removal from no-till corn plots. *Soil Science*, **171**, 468–482.
- Blanco-Canqui H, Lal R, Post WM, Izaurrealde RC, Owens LB (2006b) Corn stover impacts on near-surface soil properties of no-till corn in Ohio. *Soil Science Society of America Journal*, **70**, 266–278.
- Blanco-Canqui H, Lal R, Post WM, Izaurrealde RC, Shipitalo MJ (2007) Soil hydraulic properties influenced by corn stover removal from no-till corn in Ohio. *Soil and Tillage Research*, **92**, 144–155.
- Broadbent FE (1947) Nitrogen release and carbon loss from soil organic matter during decomposition of added plant residues. *Soil Science Society of America Proceedings*, **12**, 246–249.
- Cheng W, Johnson DW, Fu S (2003) Rhizosphere effects on decomposition: controls of plant species, phenology, and fertilization. *Soil Science Society of America Journal*, **67**, 1418–1427.
- Dilly O, Munch JC (2004) Litter decomposition and microbial characteristics in agricultural soils in northern, central, and southern Germany. *Soil Science and Plant Nutrition*, **50**, 843–853.
- Dilly O, Bloem J, Vos A, Munch JC (2004) Bacterial diversity in agricultural soils during litter decomposition. *Applied and Environmental Microbiology*, **70**, 468–474.
- Fontaine S, Mariotti A, Abbadie L (2003) The priming effect of organic matter: a question of microbial competition? *Soil Biology and Biochemistry*, **35**, 837–843.
- Fontaine S, Bardoux G, Abbadie L, Mariotti A (2004) Carbon input to soil may decrease soil carbon content. *Ecology Letters*, **7**, 314–320.
- Goering HK, Van Soest PJ (1970) *Forage Fiber Analysis: Apparatus, Reagents, Procedures and Some Applications*. USDA, Washington, DC.
- Graham RL, Perlack RD, Wright LL, Nelson R, Sheehan J (2007) Current and potential U.S. corn stover supplies. *Agronomy Journal*, **99**, 1–11.
- Kätterer T, Bolinder MA, Andrén O, Kirchmann H, Menichetti L (2011) Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture, Ecosystems & Environment*, **141**, 184–192.
- Kim S, Dale BE (2004) Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy*, **26**, 361–375.
- Kochsiek AE, Knops JM, Walters DT, Arkebauer TJ (2009) Impact of management on decomposition and the litter-carbon balance in irrigated and rainfed no-till agricultural systems. *Agricultural and Forest Meteorology*, **149**, 1983–1993.
- Kuzyakov Y, Friedel JK, Stahr K (2000) Review of mechanisms and quantification of priming effects. *Soil Biology & Biochemistry*, **32**, 1485–1498.

- Lyon DJ, Monz CA, Brown RE, Metherell AK (1997) Soil organic matter changes over two decades of winter wheat-fallow cropping in Western Nebraska. In: *Soil Organic Matter in Temperate Agroecosystems. Long-Term Experiments in North America*. (eds Paul EA, Elliot ET, Paustain K, Cole CV), pp. 343–352. CRC Press, Inc., Boca Raton, FL.
- Mcmahon SK, Williams MA, Bottomley PJ, Myrold DD (2005) Dynamics of microbial communities during decomposition of carbon-13 labeled ryegrass fractions in soil. *Soil Science Society of America Journal*, **69**, 1238–1247.
- 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.
- Rhoton FE, Shipitalo MJ, Lindbo DL (2002) Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. *Soil and Tillage Research*, **66**, 1–11.
- Rubino M, Dungait JAJ, Evershed RP *et al.* (2010) Carbon input belowground is the major C flux contributing to leaf litter mass loss: evidences from a C-13 labelled-leaf litter experiment. *Soil Biology & Biochemistry*, **42**, 1009–1016.
- Van Soest PJ, Robertson JB, Lewis BA (1991) Methods for dietary fiber neutral detergent fiber and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science*, **74**, 3583–3597.
- Verma SB, Dobermann A, Cassman KG *et al.* (2005) Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology*, **131**, 77–96.
- Wu J, Brookes PC, Jenkinson DS (1993) Formation and destruction of microbial biomass during decomposition of glucose and ryegrass in soil. *Soil Biology & Biochemistry*, **25**, 1435–1441.