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Corn Cob Residue Carbon and Nutrient Dynamics during Decomposition

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ABSTRACT

The cob fraction of corn (*Zea mays* L.) residue has characteristics that reduce concerns associated with residue removal making it a potential biofuel feedstock. The contribution the cob makes to soil C and nutrient dynamics is unknown. A litterbag study was conducted in no-tillage plots under irrigated and rainfed conditions in eastern Nebraska. Litterbags containing cobs were placed in corn rows on the soil surface or vertically in the 0- to 10-cm soil depth following grain harvest and collected after 63, 122, 183, 246, 304, and 370 d. Samples were analyzed for dry matter, C, N, P, K, S, Ca, Mg, Fe, Mn, Cu, and Zn. Dry matter loss was greater for buried (59% loss rainfed site vs. 64% irrigated site) than surface cobs (49% loss rainfed site vs. 42% irrigated site). Cob N, P, S, content did not change over the duration of the study and these nutrients would play a limited role in nutrition for the subsequent crop. Cob K content declined exponentially over the study suggesting that cob K would be available to the subsequent crop. Cob Ca, Mg, Zn, Fe, Mn, and Cu content increased during the study representing immobilization. With the exception of K, nutrients contained in the cob are immobilized the year following harvest and play a minor role in mineral nutrition of the subsequent crop. As cellulosic conversion technology becomes available cobs represent a feedstock that can be harvested with minor effect on crop nutrient availability.

Crop residue has been proposed as a feedstock for biofuel production (Perlack et al., 2005). Concerns associated with crop residue removal include an increase in nutrient removal, the potential for soil compaction due to additional field activities, an increase in the potential for wind and water erosion, and a potential reduction in soil organic matter (Wilhelm et al., 2004). To address some of these concerns efforts were undertaken to estimate the amount of residue that is needed to be retained to protect the soil from wind and water erosion and that needed to sustain the soil biota and maintain soil organic matter (Johnson et al., 2006; Wilhelm et al., 2007). More recently, the distribution of dry matter and nutrients within a standing corn crop were determined so that dry matter and nutrient removal rates could be estimated as a function of harvest height (Johnson et al., 2010; Wilhelm et al., 2011). One component of corn residue that is being considered as a feedstock is the cob. The cob represents 20% of standing residue by weight (Varvel and Wilhelm, 2008), can potentially be collected during the grain harvest operation (Hoskinson et al., 2007; Shinners et al., 2007), and is being considered as a primary feedstock for a cellulosic ethanol plant (http://www.projectliberty.com/ verified 19 May 2011).

As a component of crop residue the cob provides surface cover and contains C and nutrients. Therefore cobs play a role in soil and water conservation and in soil C and nutrient dynamics. A rainfall simulator study compared runoff, sediment, and nutrient loss from plots and found that cob removal did not affect erosion or runoff and nutrient loss (Wienhold and Gilley, 2010). Burgess et al. (2002) compared dry matter loss of cobs buried or placed on the soil surface in three tillage systems and found that dry matter loss was greater for buried cobs than for those placed on the soil surface (60 vs. 32%). Burgess et al. (2002) determined initial chemical characteristics of the cob but did not follow nutrient dynamics during the decomposition process. The objective of the present study was to determine C and nutrient dynamics during the year after harvest for surface and buried cobs.

MATERIALS AND METHODS

The study was conducted at two sites in eastern Nebraska. The rainfed site was located at the University of Nebraska Rogers Memorial Farm 10 km east of Lincoln, NE. Soil at the site is a Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls). This study used four no-tillage continuous corn plots that were part of a tillage system study initiated in 1986 (Wilhelm and Wortmann, 2004). Corn (Pioneer 33M16)[1] was planted at a density of 58,000 seeds per hectare. Glyphosate (*N*-(phosphonomethyl) glycine) was applied to corn as needed to control weeds. Nitrogen was broadcast at 168 kg ha^{-1} as ammonium nitrate (34% N). Other plant nutrients were within optimum levels for corn. Corn was harvested after reaching physiological maturity and yielded 5.81 Mg ha^{-1} in 2008.

The irrigated site was located at the University of Nebraska Agricultural Research and Development Center near Mead, NE. Soils at the site are Tomek silt loam (fine, smectitic, mesic Pachic Argiudolls) and Filbert silt loam (fine, smectitic, mesic Vertic Argialbolls). This study used four no-tillage irrigated continuous corn plots that were part of a residue removal study.

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[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Corn (Pioneer 33M16) was planted at a density of 74,000 seeds per hectare. Glyphosate was applied to corn as needed to control weeds. Nitrogen was broadcast at 202 kg ha^{-1} as ammonium nitrate (34% N). Irrigation was applied through a lateral move sprinkler system. Corn was harvested after reaching physiological maturity and yielded 8.78 Mg ha^{-1} in 2008.

Ears from a no-tillage plot at the irrigated site were hand picked, shelled, and air dried for use in this study. Cob pieces used were similar in size to those distributed in a field following grain harvest with a combine. Cob material (30 g dry matter) was placed in each of 96 litter bags. On 8 Dec. 2008 one set of six bags was placed on the surface and a second set of six bags was inserted vertically in the 0- to 10-cm soil layer of each plot at each site. Remaining bags served as the time 0 sample. Litter bags were collected 63, 122, 183, 246, 304, and 370 d after being placed in the field. Soil temperature was recorded every 4 h using a Hobo temperature data logger (Onset Computer Corp., Bourne, MA) installed at the 5-cm depth. Degree days were calculated by summing average daily soil temperatures (Honeycutt and Potaro, 1990). Daily temperatures below zero were assigned a value of zero. Precipitation was recorded at the nearest weather station. Irrigation dates and amounts were also recorded.

Cob quality was assessed by analyzing the initial cob material for neutral detergent fiber, acid detergent fiber, acid detergent lignin, and ash content using a fiber analysis procedure described by Vogel et al. (1999) and nutrient concentration as described below. For subsequent collection dates material remaining in the litter bag was oven dried, weighed, and ground. A subsample was placed in a muffle furnace and ash content determined. Ash content was used to correct dry matter mass for soil adhering to the samples (Schuman and Belden, 1991). For each cob sample dry matter loss, C, N, P, K, S, Ca, Mg, Mn, Cu, Fe, and Zn concentration was determined. Cob samples were analyzed for total C and N by dry combustion (Schepers et al., 1989). Cob mineral element concentration was determined in acid digests using inductively coupled plasma spectroscopy (Peters, 2007).

Results are reported on an areal basis. Initial cob mass at each site was estimated using the cob/grain ratio reported by Varvel and Wilhelm (2008). Dry matter loss and nutrient concentration measured in the litter bag samples was then used to calculate the dry matter and nutrient content for each sampling time. Repeated measures analysis of variance was used to determine differences in dry matter, nutrient concentration, and nutrient content among sites, sampling dates, and between surface and buried cobs (SAS Institute, 1985). At both sites the experimental design was randomized blocks with four replications. The SLICE option of the LSMEANS statement was used to detect differences between depths at each site and differences over time at each site × depth combination. Differences were declared significant at the 0.05 probability level.

RESULTS

Initial Cob Residue Quality

Initial nutrient concentrations for cobs used in this decomposition study were 453 g C kg^{-1}, 3.7 g N kg^{-1}, 0.3 g P kg^{-1}, 11.5 g K kg^{-1}, 0.3 g S kg^{-1}, 0.4 g Ca kg^{-1}, 0.2 g Mg kg^{-1}, 13.0 mg Zn kg^{-1}, 190 mg Fe kg^{-1}, 8.0 mg Mn kg^{-1}, and 3.3 mg Cu kg^{-1}. Based on fiber analysis cob composition consisted of 124 g kg^{-1} of soluble cell material, 422 g kg^{-1} of hemicellulose, 356 g kg^{-1} of cellulose, 80 g kg^{-1} of lignin and cutin, and 18 g kg^{-1} of ash.

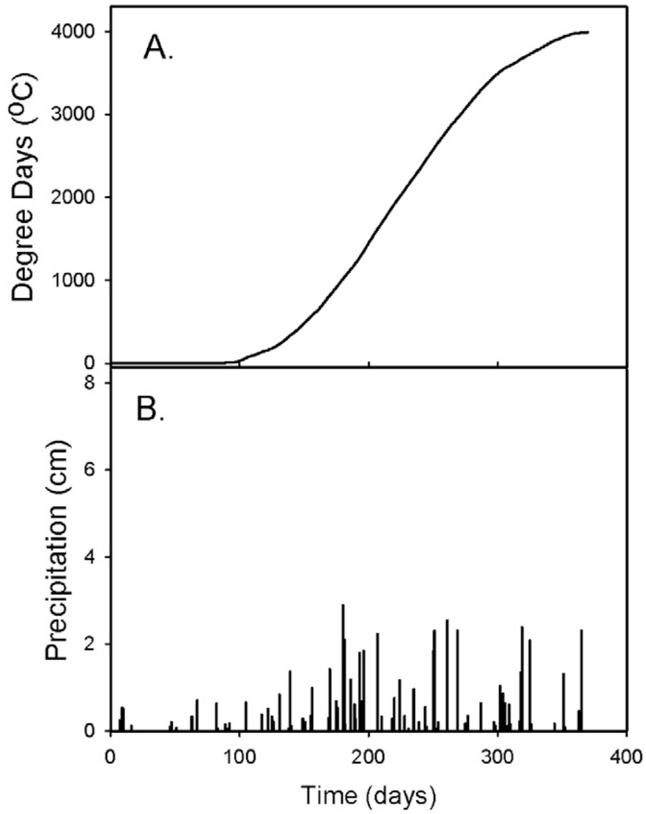

Fig. 1. (A) degree days and (B) daily precipitation as a function of time for the rainfed research site near Lincoln, NE.

Environmental Conditions

Soil temperatures were low when the litter bags were placed in the field in the fall of 2008 and degree days accumulated slowly at the rainfed site (Fig. 1A). Beginning on Day 100 soil temperatures increased and degree days accumulated linearly during the growing season before leveling off in the fall 2009. Degree days totaled 3992°C over the course of the study at the rainfed site. Over the course of the study, a total of 62.0 cm of precipitation was received at this site (Fig. 1B). The pattern in degree day accumulation at the irrigated site was similar to that at the rainfed site with low soil temperatures at the time of litter bag placement and a linear increase during the growing season (Fig. 2A). Degree days totaled 3738°C over the course of the study at this site. Precipitation at this site was supplemented with three irrigation events resulting in water inputs totaling 81.7 cm over the course of the study (Fig. 2B).

Dry Matter and Carbon

Cob dry matter was greater at the irrigated site than at the rainfed site due to greater productivity (Fig. 3A). Cob dry matter decreased with time at both sites with the decrease being greater for buried cobs than for surface cobs (Table 1). Nearly 13% of dry matter loss at the rainfed site and 15% of dry matter loss at the irrigated site occurred during the first two sampling periods when soil temperatures were low and little biological activity is expected (Fig. 3B). The rainfed site received 4.0 cm and the irrigated site received 6.25 cm of precipitation during these first two sampling periods. After one growing season 49% of surface cobs and 59%

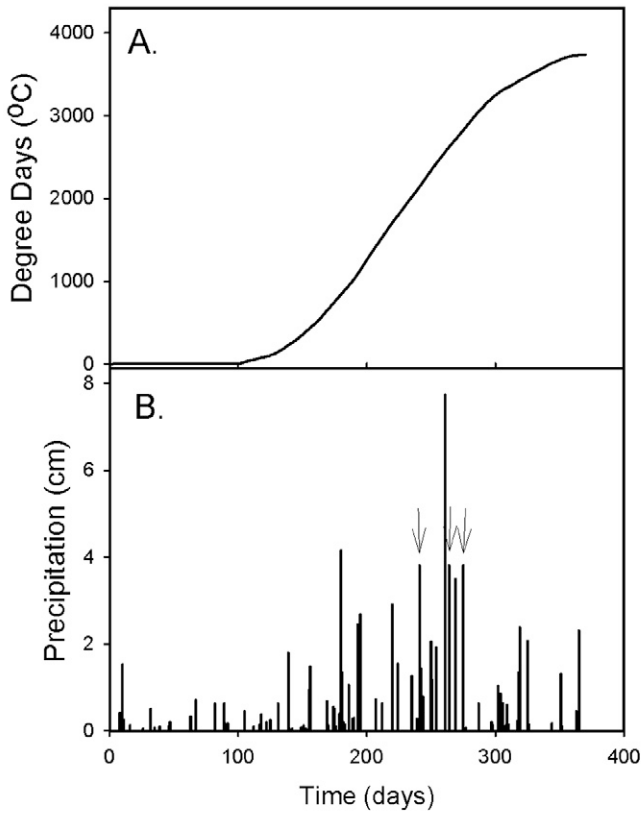

Fig. 2. (A) degree days and (B) daily precipitation and irrigation (↓) as a function of time for the irrigated reseach site near Mead, NE.

of the buried cobs was lost at the rainfed site. At the irrigated site 42% of surface cobs and 64% of buried cobs was lost.

Initial cob C content was greater at the irrigated site than at the rainfed site (Fig. 3C). At the irrigated site cob C content was similar for buried and surface samples during the first two sample periods and then decreased more quickly in buried samples than in surface samples. At the rainfed site cob C content decreased with time and was similar for surface or buried cobs resulting in a site × depth × time interaction for cob C content (Table 1).

Nutrients

Cob N content was greater at the irrigated site than at the rainfed site. Fluctuations among sample dates resulted in a site × time interaction (Table 1). The final N content for buried and surface samples was similar to initial cob N content at both sites (Fig. 4A).

Cob P content was greater at the irrigated site than at the rainfed site (Table 1). Cob P content fluctuated among sample dates (Table 1) but initial and final cob P contents were similar for surface and buried samples at both sites (Fig. 4B).

The K content in cobs, initially greater at the irrigated site than at the rainfed site, declined over time with final K contents similar for buried and surface cobs at both sites resulting in a site by time interaction (Table 1). The decline in cob K content was more rapid in buried cobs than in surface cobs resulting in a depth × time interaction (Table 1) at both sites (Fig. 4C).

Cob S content was greater at the irrigated site than at the rainfed site (Fig. 4D). Cob S content did not change during this study at the rainfed site while at the irrigated site cob S content increased slightly during the study resulting in a site × time interaction (Table 1).

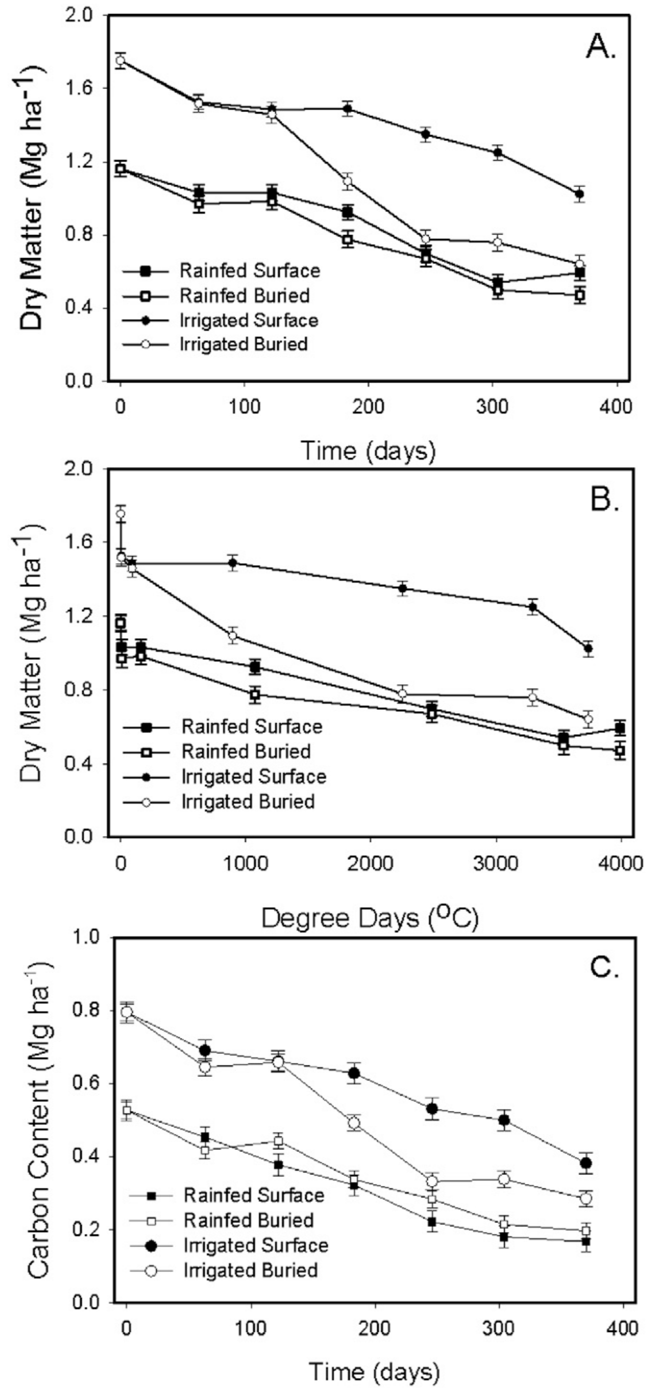

Fig. 3. Surface and buried cob dry matter as a function of (A) time and (B) degree days and (C) C content as a function of time for the irrigated and rainfed research sites in eastern Nebraska. Error bars represent standard error of the mean.

The Ca content in cobs increased over the course of the study at both sites with the increase being greater at the irrigated site than at the rainfed site resulting in a site × time interaction (Table 1). The change in Ca content was similar for surface and buried cobs at each site (Fig. 5A). Initial Mg content in cobs was greater at the irrigated site than at the rainfed site (Fig. 5B). Cob Mg content increased over time with a greater increase in surface residue than in buried residue resulting in a depth × time interaction (Table 1). Cob Zn content was greater at the irrigated site than at the rainfed site (Fig. 5C) and increased over the course of the study (Table 1). Initial cob Fe content was similar at

Table 1. Analysis of variance results for dry matter and nutrient content changes during cob decomposition.

	Dry matter	Nutrient										
Effect		C	N	P	K	S	Ca	Mg	Zn	Fe	Mn	Cu
Site (S)	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.0006	0.0004	0.0008	0.75	0.98	0.0004
Depth (D)	<0.0001	0.009	0.45	0.25	<0.0001	0.53	0.94	0.001	0.02	0.0007	0.005	0.001
S × D	0.0002	0.0006	0.07	0.34	0.0006	0.70	0.34	0.61	0.82	0.018	0.15	0.004
Time (T)	<0.0001	<0.0001	0.02	0.001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
S × T	0.002	0.04	0.0001	0.10	<0.0001	<0.0001	<0.0001	0.10	0.94	0.37	0.83	0.002
D × T	<0.0001	0.04	0.48	0.40	<0.0001	0.98	0.08	<0.0001	0.35	0.002	0.01	<0.0001
S × D × T	<0.0001	0.002	0.41	0.40	0.07	0.99	0.58	0.44	0.46	0.07	0.37	<0.0001

both sites for surface and buried cobs (Fig. 5D). Cob Fe content increased over the course of the study with a greater increase for surface cobs than for buried cobs resulting in a depth × time interaction (Table 1). Initial cob Mn content was similar at both sites and depths (Fig. 5E). Cob Mn content increased over the course of the study with a greater increase for surface cobs than for buried cobs resulting in a depth × time interaction (Table 1). Copper content was similar for surface and buried cobs at both sites for the early sampling times (Fig. 5F). Cob Cu content doubled over the remainder of the study for surface and buried cobs at the rainfed site and for surface cobs at the irrigated site but rose nearly fivefold in buried cobs at the irrigated site resulting in a site × depth × time interaction (Table 1).

DISCUSSION

This study determined dry matter, C, and nutrient dynamics during decomposition of corn cobs to better understand the impact cob harvest may have on soil C and soil fertility. The study was conducted at two continuous corn no-tillage sites that differed in water inputs. A previous study documented that irrigated soils were cooler and moister than rainfed soils under these conditions (Wienhold et al., 2009). Soil temperatures measured during the current study resulted in a pattern in degree day accumulation typical for a temperate location (Douglas and Rickman, 1992) with degree day accumulation at the irrigated site being lower than at the rainfed site. While there were similarities in dry matter loss and nutrient change patterns between the sites differences in soil conditions resulted in important differences.

At both sites there was a loss of 13 to 15% of dry matter during the first two sampling periods when soil temperatures were low and little biological activity is expected (Fig. 3). The sites received between 4 and 6 cm of precipitation during this time and the dry matter loss was likely a physical process where soluble material was leached from the cobs. The amount of dry matter lost during this time period agrees well with the 12% soluble cellular material estimated by the fiber analysis of the cobs. Rapid loss of soluble residue components is a common observation in decomposition studies (Singh and Gupta, 1977). Once degree days began to accumulate dry matter loss was greater for buried cobs than for surface cobs at both sites but the difference in dry matter loss between surface and buried cobs was greater at the irrigated site than at the rainfed site (22 vs. 10%). More rapid decomposition of buried cobs has been previously reported (Burgess et al., 2002). Buried cobs are in closer association with soil and therefore more available to soil microorganisms (Doran, 1980). Surface cobs at both sites likely dried out quickly after experiencing rain or irrigation events.

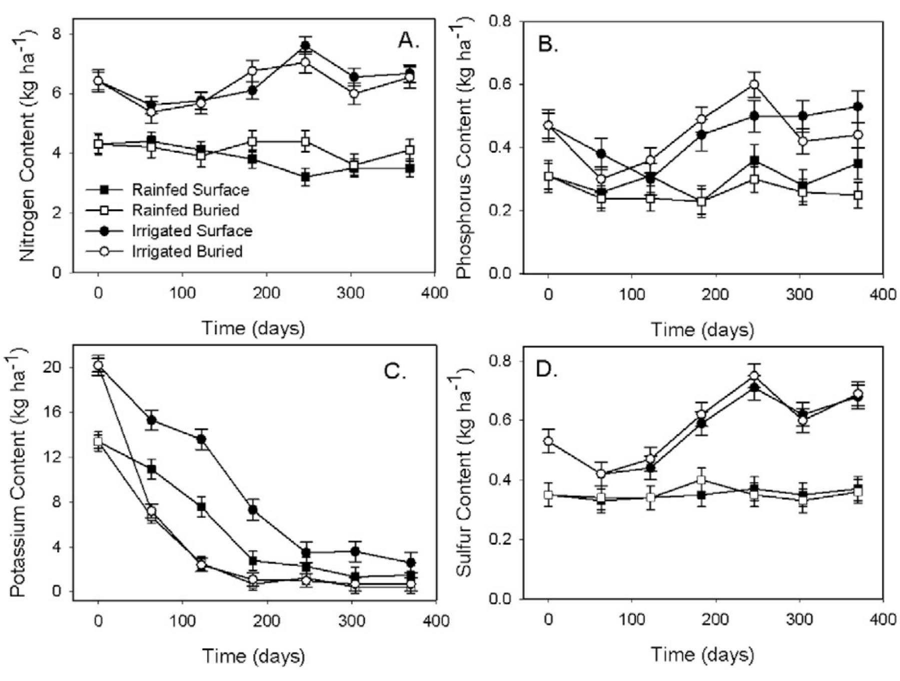

Fig. 4. Nitrogen, P, K, and S content for surface and buried cobs as a function of time for the irrigated and rainfed research sites in eastern Nebraska. Error bars represent standard error of the mean.

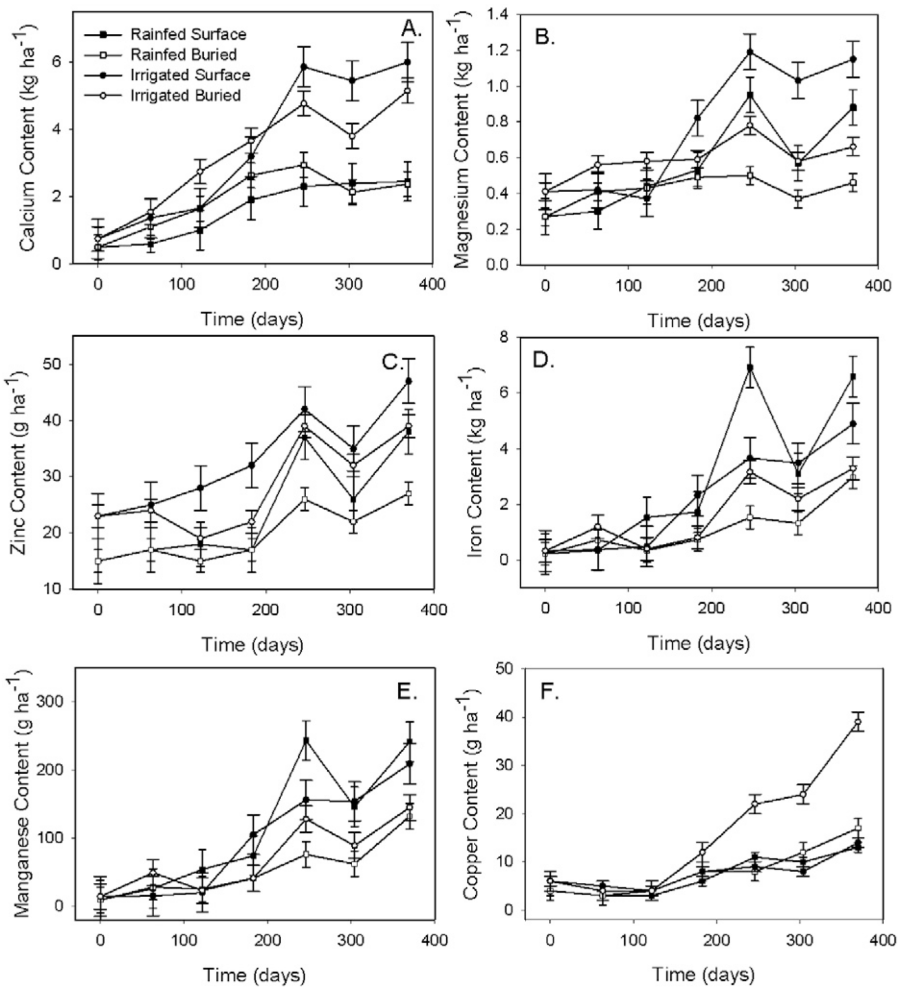

Fig. 5. Calcium, Mg, Zn, Fe, Mn, and Cu content for surface and buried cobs as a function of time for the irrigated and rainfed research sites in eastern Nebraska. Error bars represent standard error of the mean.

Buried cobs would dry more slowly and cobs at the irrigated site would likely have experienced moister conditions a greater portion of the study due to 20 cm greater water input.

Nutrient concentration and composition of residue are often used to describe residue quality in decomposition studies (Collins et al., 1990). The soluble cell material, lignin concentrations, and initial C/N ratio of cob residue in this study are slightly lower than those reported by Burgess et al. (2002). In this study initial cob C and S concentrations are similar and N, P, and K concentrations are lower than those reported by Johnson et al. (2010) across eight locations in the United States (450 g C kg^{-1}, 5.5 g N kg^{-1}, 0.5 g P kg^{-1}, 6.2 g K kg^{-1}, and 0.3 g S kg^{-1}). As the cobs decomposed the C/N ratio declined from 122 to 60. The decline in cob C content over time represents respiration losses as soil microorganisms break down the residue (Johnson et al., 2007). While C content declined as C compounds in the residue were being used as energy sources by soil microorganisms N, P, and S content did not change suggesting that little N, P, and S would be available to a growing crop during the first year of cob decomposition. These results differ from those of Alberts and Shrader (1980) who reported a decline in N and P content for stalk and leaf residue during the first year of decomposition. In contrast, cob K content declined with most of the loss in K occurring during the first two sampling periods when biological activity was limited by low soil temperatures. As K was lost from the cobs it likely would occupy exchange sites in the soil and would become part of the available K pool the following growing season. Removal of cobs for use as a feedstock would have resulted in the loss of 12.5 kg K ha^{-1} at the rainfed site and 18.5 kg K ha^{-1} at the irrigated site. We are not aware of other studies determining the fate of K and S during cob decomposition.

Table 2. Nutrients removed from a 9 Mg ha^{-1} corn crop assuming 100% grain removal, 50% stover removal, or 100% cob removal.

Nutrient	Grain†	Stover‡	Cobs
Dry matter, Mg ha^{-1}	9.0	4.5	1.8
C, Mg ha^{-1}	4.1	1.9	0.8
N, kg ha^{-1}	141	29	7
P, kg ha^{-1}	29	5	0.5
K, kg ha^{-1}	40	48	21
S, kg ha^{-1}	10	2	0.5
Ca, kg ha^{-1}	3	16	4
Mg, kg ha^{-1}	11	9	0.4
Fe, g ha^{-1}	489	600	342
Zn, g ha^{-1}	218	135	23
Mn, g ha^{-}	71	135	14
Cu, g ha^{-1}	23	14	6

† Grain nutrient removal calculated using grain nutrient concentrations reported in National Resource Council (2000).

‡ Stover nutrient removal calculated using stover nutrient concentrations reported in Johnson et al. (2010).

Other nutrients assessed at this site (Ca, Mg, Zn, Fe, Mn, and Cu) changed little in content during early sample periods and then accumulated over the course of the study. One possible explanation for the accumulation of micronutrients in the cobs is contamination by soil adhering to the residue. Little soil adhered to buried cobs as these were always relatively moist when collected and associated soil was easily dislodged. Surface cobs dried out more quickly and soil adhered more strongly. Ash content of surface cobs from the irrigated site was double and from the irrigated site was fourfold that of buried cobs. Accumulation of Ca, Mg, Zn, Fe, Mn, and Cu in cobs did not follow a consistent pattern (Fig. 5). The accumulation patterns exhibited by Fe (Fig. 5D) and Mn (Fig. 5E) most closely resemble ash content and soil contamination may explain the increase over the course of the study. For Ca, Mg, Zn, and Cu accumulation tended to be greater in cobs at the irrigated site than at the rainfed site and greater in buried cobs than in surface cobs which are opposite the trends in ash content. In addition to soil contamination, processes such as leaching and bioaccumulation may have played a role in the accumulation pattern exhibited by micronutrients in this study. More detailed methods than those used in this study will be needed assess these processes. We know of no studies reporting nutrient dynamics during cob decomposition.

One of the concerns associated with use of crop residue as a biofuel feedstock relates to the removal of nutrients and a potential decline in soil fertility over time. Grain removal during crop production removes significant amounts of nutrients (Table 2). Harvesting stover for use as a biofuel feedstock, assuming 50% removal, would result in additional nutrient removal of 20 to 120% that of grain for nutrients N, P, K, and S. Removal of other nutrients in stover ranges from 60% for Zn and Cu to ~500% for Ca when compared to that removed in the grain. In contrast, the lower mass of dry matter removed combined with the lower concentration of nutrients in cobs than in stalks and leaves results in removal of fewer nutrients with cob removal than removal of other stover components (Table 2).

Cob mass is 17 to 20% of grain mass (Halvorson and Johnson, 2009; Varvel and Wilhelm, 2008) and based on an average national yield of 257 million Mg corn grain from 2005 to 2009 (http://www.nass.usda.gov/ verified 19 May 2011) cobs represent a 40 to 50 million Mg yr^{-1} feedstock. Results from the present study show that with the exception of K nutrients in cobs are retained during the first year of decomposition and would have limited availability to the subsequent crop. In addition, harvesting cobs results in lower nutrient removal rates than when other stover components are included in the harvest. As cob harvesting technology is developed and cellulosic conversion processes are developed cobs have potential to be a significant feedstock with minor effect on crop nutrient availability.

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REFERENCES

Alberts, E.E., and W.D. Shrader. 1980. Cornstalk decomposition on a till-planted watershed. Agron. J. 72:709–712. doi:10.2134/agronj1980.00021962007200050004x

Burgess, M.S., G.R. Mehuys, and C.A. Madramootoo. 2002. Decomposition of grain-corn residues (*Zea mays* L.): A litterbag study under three tillage systems. Can. J. Soil Sci. 82:127–138. doi:10.4141/S01-013

Collins, H.P., L.F. Elliot, R.W. Rickman, D.F. Bezdicek, and R.I. Papendick. 1990. Decomposition and interactions among wheat residue components. Soil Sci. Soc. Am. J. 54:780–785. doi:10.2136/sssaj1990.03615995005400030026x

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765–771. doi:10.2136/sssaj1980.03615995004400040022x

Douglas, C.L., Jr., and R.W. Rickman. 1992. Estimating crop residue decomposition from air temperature, initial nitrogen content, and residue placement. Soil Sci. Soc. Am. J. 56:272–278. doi:10.2136/sssaj1992.03615995005600010042x

Halvorson, A.D., and J.M.F. Johnson. 2009. Corn cob characteristics in irrigated Central Great Plains studies. Agron. J. 101:390–399. doi:10.2134/agronj2008.0142x

Honeycutt, C.W., and L.J. Potaro. 1990. Field evaluation of heat units for predicting crop residue carbon and nitrogen mineralization. Plant Soil 125:213–220. doi:10.1007/BF00010659

Hoskinson, R., D.L. Karlen, S.J. Birrell, C.W. Radtke, and W.W. Wilhelm. 2007. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass Bioenergy 31:126–136. doi:10.1016/j.biombioe.2006.07.006

Johnson, J.M.F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622–636. doi:10.2134/agronj2005.0179

Johnson, J.M.F., N.W. Barbour, and S. Lachnicht Weyers. 2007. Chemical composition of crop biomass impacts its decomposition. Soil Sci. Soc. Am. J. 71:155–162. doi:10.2136/sssaj2005.0419

Johnson, J.M.F., W.W. Wilhelm, D.L. Karlen, D.W. Archer, B. Wienhold, D.T. Lightle, D. Laird, J. Baker, T.E. Ochsner, J.M. Novak, A.D. Halvorson, F. Arriaga, and N. Barbour. 2010. Nutrient removal as a function of corn stover cutting height and cob harvest. Bioenerg Res. 3:342–352. doi:10.1007/s12155-010-9093-3

National Resource Council. 2000. Nutrient requirements of beef cattle. 7th ed. Update. Natl. Academy Press, Washington, DC.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erback. 2005. Biomass as a 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. Available at http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf (verified 19 May 2011). NTIS, Springfield, VA.

Peters, J.B. 2007. Wisconsin procedures for soil testing, plant analysis and feed & forage Aanalysis. Dep. of Soil Sci., College of Agriculture and Life Sciences, Univ. of Wisconsin-Ext., Madison. Available at http://uwlab.soils.wisc.edu/procedures.htm (verified 19 May 2011).

SAS Institute. 1985. SAS user's guide. SAS Inst., Cary, NC.

Schepers, J.S., D.D. Francis, and M.T. Thompson. 1989. Simultaneous determination of total C, total N, and ^{15}N on soil and plant material. Commun. Soil Sci. Plant Anal. 20:949–959. doi:10.1080/00103628909368128

Schuman, G.E., and S.E. Belden. 1991. Decomposition of wood-residue amendments in revegetated bentonite mine spoils. Soil Sci. Soc. Am. J. 55:76–80. doi:10.2136/sssaj1991.03615995005500010013x

Shinners, K.J., G.S. Adsit, B.N. Binversie, M.F. Digman, R.E. Muck, and P.J. Weimer. 2007. Single-pass, split stream harvest of corn grain and stover. Trans. ASABE 50:355–363.

Singh, J.S., and S.R. Gupta. 1977. Plant decomposition and soil respiration in terrestrial ecosystems. Bot. Rev. 43:449–528. doi:10.1007/BF02860844

Varvel, G.E., and W.W. Wilhelm. 2008. Cob biomass production in the Western Corn Belt. Bioenergy Res. 1:223–228. doi:10.1007/s12155-008-9026-6

Vogel, K.P., J.F. Pedersen, S.D. Masterson, and J.J. Toy. 1999. Evaluation of a filter bag system for NDF, ADF, and IVDMD forage analysis. Crop Sci. 39:276–279. doi:10.2135/cropsci1999.0011183X003900010042x

Wienhold, B.J., and J.E. Gilley. 2010. Cob removal effect on sediment and runoff nutrient loss from a silt loam soil. Agron. J. 102:1448–1452. doi:10.2134/agronj2010.0202

Wienhold, B.J., G.E. Varvel, and W.W. Wilhelm. 2009. Container and installation time effects on soil moisture, temperature, and inorganic nitrogen retention for an in situ nitrogen mineralization method. Commun. Soil Sci. Plant Anal. 40:2044–2057. doi:10.1080/00103620902960575

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: A literature review. Agron. J. 96:1–17. doi:10.2134/agronj2004.0001

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. doi:10.2134/agronj2007.0150

Wilhelm, W.W., J.M.F. Johnson, D.T. Lightle, D.L. Karlen, J.M. Novak, N.W. Barbour, D.A. Laird, J. Baker, T.E. Ochsner, A.D. Halvorson, D.W. Archer, and F. Arriaga. 2011. Vertical distribution of corn stover dry mass grown at several US locations. BioEnergy Res. 4:11–21. doi:10.1007/s12155-010-9097-z

Wilhelm, W.W., and C.S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron. J. 96:425–432. doi:10.2134/agronj2004.0425