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Long-term Effects of Aboveground Biomass Removal by Burning on Potential Nutrient Recycling

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Abstract
Removing aboveground biomass for dedicated bioenergy production has received much attention recently. However, potential long-term impacts of annual aboveground biomass removal on soil and environmental quality have received much less attention and are generally not well documented. A 7-year study was conducted to estimate long-term differences in potential annual recycling of plant-derived nutrients back to the soil, relative to that removed from the system in wheat grain removal, as affected by burning a high and low level of wheat (*Triticum aestivum* L.) residue achieved with differential N fertilization. Elemental mass balances were performed to estimate the net input or loss of a suite of plant-derived nutrients based on nutrients removed in wheat grain and returned to the soil surface in the aboveground residue after harvest. Results demonstrated that annual removal of aboveground residue by burning has a substantial negative impact on the potential organic C and a smaller, though still negative, impact on P available for recycling back to the soil. It is imperative that new cultural practices that have the potential to negatively affect soil nutrient pools, such as the annual removal of aboveground biomass as a bioenergy feedstock, be carefully considered before they are recommended for wide spread adoption.

Introduction
Returning plant residues to the soil where water and nutrients were extracted to produce aboveground biomass is a natural mechanism to recycle a portion of those nutrients. This process also provides the input of a valuable and necessary C and energy source to soil microorganisms that carry out the decomposition of organic matter and release of nutrients back to the system (26). It has long been known that addition of organic residues with subsequent increase in soil organic matter provides a variety of positive physical, chemical, and biological benefits to the soil-plant environment (29), such as: decreasing soil bulk density; increasing porosity, water-holding capacity, aggregate stability, and soil organic carbon (SOC) content; and increasing the diversity and mass of the soil microorganism community to name a few (28). Therefore, decreasing the return of organic matter to the soil by harvest and removal of aboveground biomass could be detrimental in the long term to the soil resource (4), particularly to the SOC content (30), with negative impact on the sustainability of the entire system (28). One such recently developed agricultural enterprise that could have a major impact on soil organic matter and potential long-term sustainability is the possible widespread shift to production of dedicated bioenergy crops.

States comprising the Lower Mississippi River Valley (i.e., Missouri, Arkansas, Kentucky, Tennessee, and Mississippi) have been recently recognized as having substantial bioenergy production potential (31), including the production of lignocellulosic feedstocks such as switchgrass (*Panicum virgatum* L.), due in part to the favorable regional climate, long growing season, and long history of highly productive agricultural enterprises. Annual aboveground dry matter yields for switchgrass have been reported to vary between 5 and 10 Mg/ha for upland and between 9 and almost 15 Mg/ha for lowland ecotypes

(34,38). However, long-term field trials with switchgrass and other potential cellulosic feedstocks that have evaluated the potential negative impacts of annual aboveground biomass removal on soil properties are rare (4). Furthermore, environmental implications of potential cellulosic feedstocks for bioenergy production, in general, are poorly understood (4,11,34).

Of the major cereal crops produced in the United States, wheat resembles switchgrass in growth habit, stature, and other physiological characteristics (35), nutrient and water requirements (35), and dry matter production and has the most similar management and production practices (25,34). Based on 10 years of variety trails conducted from 2001 to 2010 (3,13,14,15,16,17,18,19,20,21) and assuming a typical harvest index of 0.5 (R. K. Bacon, 2011, *personal communication*), total aboveground wheat dry matter production ranged from 5 to 10 Mg/ha and averaged 7.5 Mg/ha across multiple locations in Arkansas. These wheat dry matter yields approximate the total aboveground dry matter production of switchgrass (38). Consequently, understanding annual aboveground wheat biomass removal (22), commonly accomplished in the Mid South by burning, could provide insight into potential negative implications of long-term annual aboveground biomass removal from large-scale bioenergy crop production systems.

Therefore, the objective of this study was to estimate long-term differences in potential nutrients recycled back to the soil, relative to that removed by wheat grain harvest, in response to annual aboveground biomass removal by burning a high and low level of wheat residue in a wheat-soybean [*Glycine max* (L.) Merr.] double-crop production system in eastern Arkansas. It was hypothesized that five years of aboveground wheat biomass removal by burning will decrease the amount of potential C and other essential plant nutrients recycled back to the soil in the crop residue.

Site Description

A wheat-soybean, double-crop rotation was established in fall 2001 (7) at the Lon Mann Cotton Branch Research Station (34°44'2.26"N, 90°45'51.56"W) near Marianna, AR, on a Calloway silt-loam soil (fine-silty, mixed, active, thermic, Aquic Fraglossudalf) (6,10,33). The study area was divided into 48 3-×-6-m plots. Prior to fall 2001, the study area had been under conventionally tilled soybean production for several years.

Field Experiment

Each fall in early November from 2001 through 2008, wheat (Coker 9553) was drill-seeded at a rate of 90 kg seed/ha in 19-cm-wide rows (i.e., approximately 20 seeds/ft^2). The following spring each year, wheat was manually broadcast-fertilized with two different N rates to achieve contrasting amounts of surface residue into which the subsequent soybean crop was planted. Between 2002 and 2004, all plots were fertilized in mid March with 101 kg N/ha as dry urea. After approximately one month, one half of the plots were fertilized with a second application of 101 kg N/ha as dry urea. The imposed differential fertilization scheme created a low and high N rate/residue level treatment (6,8). Between 2006 and 2008, all high N rate/residue level plots were fertilized in approximately mid March with 56 kg N/ha and received a second application of 56 kg N/ha as urea approximately one month later. Between 2006 and 2008, the low N rate/residue level plots received no N applications. Due to prolonged wet-soil conditions in fall 2004, no wheat stand was produced in 2005 and plots were left fallow until prior to the subsequent soybean crop.

Wheat was harvested in early June each year with a plot combine. Following harvest each year, wheat stubble was mowed with a 3-m wide rotary mower to an approximate height of 10 cm to achieve a relatively uniform distribution of wheat residue within each plot. After mowing, aboveground residue in half of the plots was burned by propane flaming, while aboveground residue in the remaining plots was left unburned. The burn treatment was arranged in a randomized complete block with two replications (8). All plots in the burned treatment were separated from any non-burned plots by a 40-ft alley that was tilled before burning to minimize translocation of plant biomass and/or ash across treatments and for safety reasons. Following imposition of the burn treatment, one half of the plots were conventionally tilled (CT) perpendicular to wheat rows with three passes with a tandem disk to a depth of between 5 and 8 cm followed by three passes with a rolling-harrow soil conditioner (similar to that by Unverferth Manufacturing Co. Inc., Kalida, OH) to prepare a smooth seed bed. The remaining one half of the plots were left untilled to constitute a no-tillage (NT) treatment. The tillage treatment was arranged as a randomized complete block stripped across the burn treatment with three replications (8).

A glyphosate-resistant soybean cultivar, maturity group 5.3 in 2002 through 2005 and maturity group 5.4 in 2006 through 2008, was drill-seeded parallel to wheat rows in mid to late June each year at a rate of 101 kg seed/ha with a 19-cm row spacing. During the soybean growing seasons, weeds and insects were controlled according to University of Arkansas Cooperative Extension Service recommendations (8,36,37). A single application of 84 kg K/ha as KCl (75 lb/acre) was made in May 2005. Other than N applications for achieving differential residue levels, no other nutrients were added throughout the duration of this study. Soybeans were harvested in October each year with a plot combine and soybean residue returned to the plot. No field manipulations occurred between soybean harvest and subsequent wheat planting each fall.

Plant Sampling and Analyses

Plots were combine-harvested and sub-samples of wheat grain were collected annually, oven-dried, and weighed to determine wheat yields for each plot. Total mass of grain was subsequently corrected for the measured moisture content. Following mowing, but prior to burning, aboveground residue samples were collected each year from a randomly located, 0.25-m^2 area within each plot, oven-dried, and weighed to determine surface residue levels. Following residue burning, but prior to soybean planting, grab samples of ash were collected each year from the 24 burned-residue plots. Wheat grain and residue samples were mechanically ground and ash samples were manually pulverized in preparation for chemical analyses.

Total N and C were determined on oven-dried and ground or pulverized wheat grain, residue, and ash samples by high-temperature combustion. Total P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu were also determined on oven-dried and ground or pulverized wheat grain, residue, and ash samples by inductively coupled, argon-plasma spectrophotometry following digestion in a concentrated nitric acid/hydrogen peroxide solution on a heating block (27).

Data Analyses

For each of six years (i.e., 2002 through 2008, with the exception of 2005 when there was no wheat crop produced), an elemental mass balance was estimated for the burned and non-burned and low and high N rate/residue level treatment combinations. Data were averaged across tillage treatments since the annual tillage treatment was only implemented for the subsequent soybean crop and previous results from this field study have demonstrated a lack of a tillage affect on many measured properties (1,6,8). The amount (kg/ha) of N, C, P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu removed each year in the wheat grain was calculated based on measured wheat yields and elemental concentrations. The amount (kg/ha) of N, C, P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu present in the surface residue and in the resulting ash following burning were calculated based on measured residue levels or estimated ash amounts and elemental concentrations. Since consistent differences in soybean yield among burn/residue-level treatment combinations were not observed, nutrient removal from soybean grain was assumed to be similar across all treatment combinations evaluated in this study, hence it was not explicitly accounted for in the mass balance estimations. Based on personal observations, the mass reduction achieved from propane flaming of mowed wheat residue was similar to that achieved following prescribed burning of a tallgrass prairie. Therefore, based on direct quantification of biomass reduction as a result of burning a tallgrass prairie (5), burning was assumed to reduce the residue mass by 90%. Therefore, on an annual basis, the mass balance (MB) was calculated from the following equation:

$$MB = M_{fert} + M_{straw/ash} - M_{grain} - M_{burned\ straw} \quad [1]$$

where M_{fert} is the mass of elemental fertilizer added, $M_{straw/ash}$ is the elemental mass returned to the soil in the straw and/or ash, M_{grain} is the elemental mass removed in the harvested wheat grain, and $M_{burned\ straw}$ is the elemental mass removed by burning.

An average annual mass balance was determined from the six years of data to result in a net elemental change relative to that removed by the harvested wheat grain for the burned and non-burned and low and high N rate/residue level treatment combinations. Final estimated net elemental changes for the four treatment combinations were based on 12 replications per year averaged across six years. An analysis of variance was conducted using SAS (version 9.2, SAS Institute Inc., Cary, NC) to evaluate the effects of burning and wheat residue level on the annual net elemental change relative to that removed in the harvested wheat grain. Considering the original experimental design (8) was altered by averaging across the tillage treatment, a completely random design was assumed for this analysis. When appropriate, means were separated by least significant difference at the 0.05 level.

Wheat Yields

With the exception of 2005 when no wheat crop was produced, annual wheat grain yields between 2002 and 2008 ranged from 1201 to 4284 kg/ha (17.9 to 66.1 bu/acre) and averaged 42.7 bu/acre (2869 kg/ha) at 13% moisture content across all treatment combinations. Though the whole-study wheat grain yields generally declined over time (Table 1), the 6-year mean wheat grain yield was similar to the US mean of 2924 kg/ha (43.6 bu/acre), but was slightly less than the Arkansas mean of 3452 kg/ha (51.4 bu/acre) for the same time period (32). Within N rate/residue level treatments, wheat grain yields ranged from 812 to 4356 kg/ha (12.1 to 64.9 bu/acre) and averaged 2470 kg/ha (36.8 bu/acre) under a sub-optimal N fertilization scheme (i.e., the low N rate/residue level treatment) and ranged from 1591 to 4517 kg/ha (23.7 to 67.3 bu/acre) and averaged 3268 kg/ha (48.7 bu/acre) under the recommended N fertilization scheme (i.e., the high N rate/residue level treatment) for wheat grown on a silt-loam soil in Arkansas (35). Therefore, resulting plot-scale wheat grain yields observed in this study were reasonably representative of typical wheat grain yields from field-scale production practices.

Table 1. Annual and 6-year summary of mean wheat grain yields, based on 13% moisture, and residue levels (oven-dried) measured after grain harvest, but before burning.

Year/ 6-year mean	Grain yield (kg/ha)		Residue level (kg/ha)	
	Burn	No burn	Burn	No burn
2002	4460	4414	3585[x]	3585[x]
2003	4607	3575*	5152[x]	5152[x]
2004	3169	2898	6852[x]	6852[x]
2006	3112	3153	5996	11495*
2007	1197	1410	5237	5176
2008	1194	1246	8710	8591
6-year mean	2956	2783	5922	6809

* Asterisks (*) indicate a significant difference ($P < 0.01$) between burn treatments in that year for that parameter.

[x] Residue samples were not collected in the burned plots, therefore the measured residue levels from the non-burned treatment were assigned to the burn treatment.

Net Nutrient Balance Relative to that Removed by Grain Harvest

Based on the analysis presented in this study, since soil change data were not accounted for, all elements evaluated had at least small net additions to the system, with no actual net losses. Estimated net changes of all plant macro- or micro-nutrients evaluated in this study relative to that removed by grain harvest were affected by N rate/residue level, burning, or both. Nitrogen, K, and Na were significantly affected by N rate/wheat residue level ($P < 0.04$) when averaged across burn treatments. For all three elements, the high N rate/residue level had at least a two-fold greater mean annual elemental addition to the system than the low N rate/residue level treatment relative to that removed in the wheat grain (*data not shown*). For all other elements evaluated, the mean annual change relative to that removed in the wheat grain was unaffected by the N rate/residue level treatment.

With the exception of Na, net change of all other elements evaluated relative to that removed by grain harvest was significantly affected by residue burning ($P < 0.05$). Averaged across N rate/residue level, N, C, P, K, Ca, Mg, S, Fe, Mn, Zn, and Cu had greater net additions relative to that removed by grain harvest when the residue was left unburned compared to when aboveground residue was removed by burning. Net changes of Mg, S, Fe, Mn, Zn, and Cu relative to that removed by grain harvest were generally small and ranged from a low of -1.6 kg/ha/year for S to a high of 1.3 kg/ha/year for Fe when residue was removed by burning. In comparison, net annual additions of < 8 kg/ha/year relative to that removed by grain harvest were observed for the same nutrients when wheat residue was returned to the soil surface without burning.

The 6-year mean balance for C contained in wheat residue averaged 1722 kg C/ha/year greater than that removed by grain harvest when residue was left unburned (Fig. 1). However, when residue was removed by burning, 517 kg C/ha/year less than that removed by grain harvest was returned to the system for a difference between burning the residue and leaving the residue unburned of 2240 kg C/ha/year (Fig. 1). Annual aboveground residue production and wheat grain yields were both unaffected by the burn treatment in five out of six years each and the 6-year means were also unaffected by the burn treatment (Table 1). Therefore, burning clearly reduced the amount of potential C recycled back to the soil relative to the amount of C removed from the grain harvest due to the reduction of aboveground residue mass by volatilization during the burning process and some, though minimal, off-site transport of ash by light winds during burning. Furthermore, though the mean annual C concentration in the unburned residue (40.6%) was numerically greater than that in the ash following burning (35.0%), C concentrations did not differ significantly ($P > 0.1$) and averaged 37.8%, while the grain-C concentration averaged 40.8% across all treatments.

Similar to that for C, the 6-year mean balance for P was negative when residue was removed by burning, but, in contrast to that for C and all other nutrients evaluated, was also negative when residue was left unburned relative to that removed by grain harvest (Fig. 1). The amount of P added to the system on an annual basis was nearly 20 times less when residue was removed by burning than when left unburned (Fig. 1).

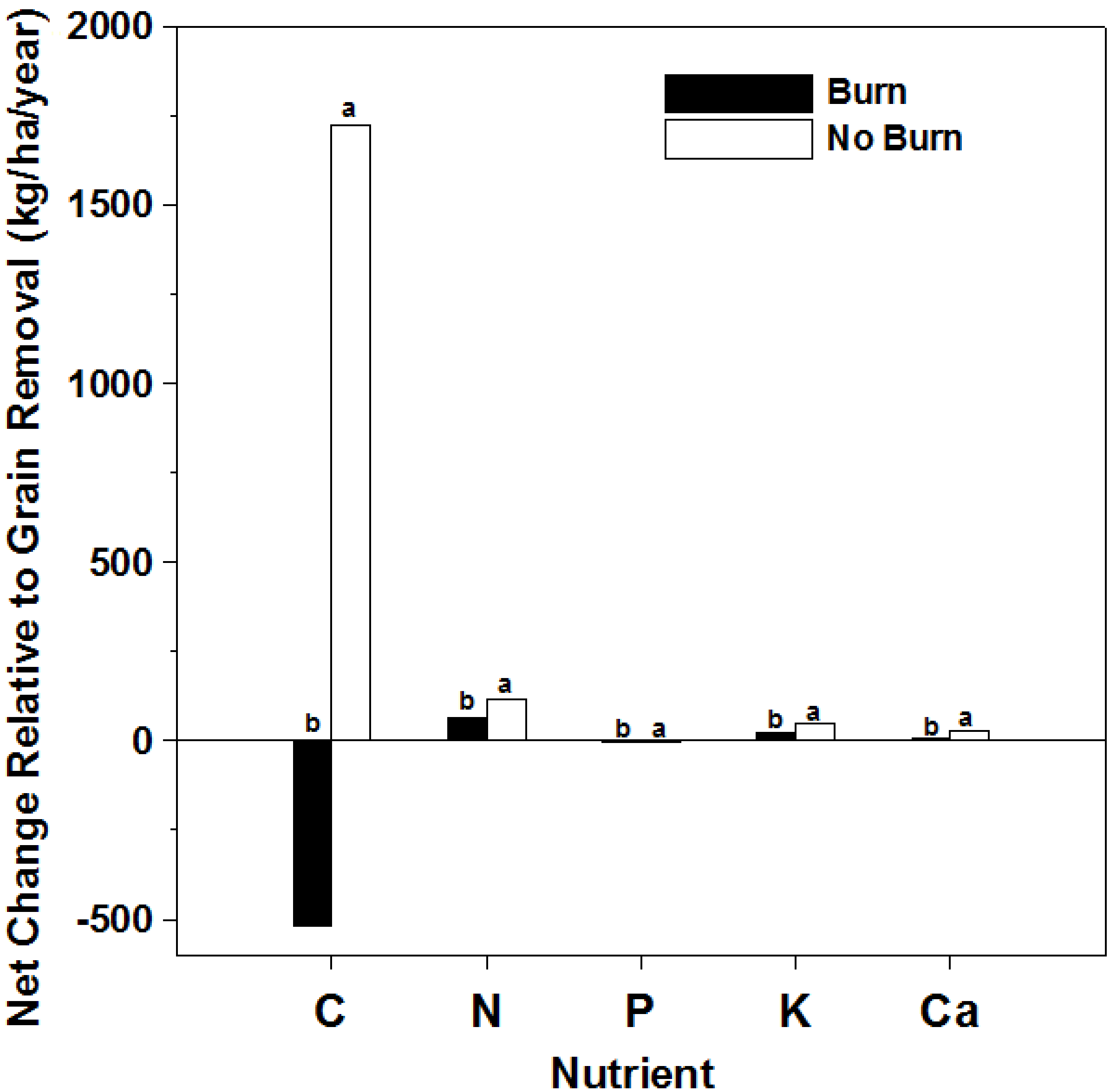

Fig. 1. Mean annual elemental change relative to that removed from grain harvest from six years of observations from burning and non-burning wheat residue averaged across wheat residue/N rate treatments in the Mississippi River Delta region of eastern Arkansas. Different lower case letters atop bars within the same element are significantly different at the 0.05 level.

Agronomic Implications

Despite small annual losses for P relative to that removed by grain harvest, results for N, P, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu observed in this study were generally agronomically inconsequential. However, though the C contained in the belowground wheat biomass still contributed an annual input of C to the soil, results of this study clearly show that annual removal of residue by burning has a substantial negative impact on potential SOC available for recycling to the soil. To further substantiate the negative impact of burning on C available for recycling to the soil, SOC content trends in the top 10 cm observed from 2002 to 2007 demonstrated a significantly lower, though still positive, SOC sequestration rate under the burned than non-burned treatment at this same study site (1). This result is consistent with other findings that have demonstrated a direct negative impact on soil organic matter from repeated residue removal (11,22,28). The presence of SOC provides many positive direct and indirect effects on soil properties and plant productivity and maintaining an adequate SOC pool is closely linked with long-term sustainability of any agronomic system (23). As a result, it is critical that new cultural practices that have the potential to decrease the SOC pool, such as annual removal of aboveground biomass as a bioenergy feedstock (2,9,12,24), be more carefully considered before they are recommended and wide spread adoption takes place. Furthermore, in contrast to other plant nutrients evaluated in this study, using inorganic fertilizers alone will likely not be sufficient to surmount decreasing SOC as a result of annual aboveground biomass removal (9), particularly in marginally productive land areas that an expanding biofuels industry would target (34). Perhaps less frequent residue removal than yearly, as was recommended by Lafond et al. (22), would be a reasonable compromise so as to help preserve long-term sustainability of the soil resource as annual residue removal clearly has a net negative effect on C cycling.

Acknowledgments

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