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John E. Gilley

USDA-ARS, john.gilley@ars.usda.gov

David B. Marx

University of Nebraska-Lincoln, david.marx@unl.edu

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Accumulation and Release of Nutrients by Immersed Stalks Collected on Selected Dates Following Harvest

John E. Gilley · David B. Marx

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Abstract The concentrations of phosphorus (P) and nitrogen (N) in runoff from cropland areas may be influenced by accumulation and release of P and N by stalk residues. A laboratory study was conducted to measure the effects of time since harvest and immersion period on accumulation and release of P and N by corn, soybean, and wheat stalks. Experimental variables included type of stalk material (corn, soybean, and wheat), time since harvest (six residue collection dates over an approximate 1-year period), and stalk immersion period (25 s (0.42 min), 250 s (4.2 min), 2500 s (42 min), 25,000 s (6.9 h), and 86,400 s (24 h)). The initial concentration of each of the P and N constituents in a test solution was $6 \mu\text{g mL}^{-1}$. The soybean, wheat, and corn residue released $\text{PO}_4\text{-P}$ at mean rates of 40, 69, and $141 \mu\text{g g}^{-1}$ residue, respectively. The amount of $\text{PO}_4\text{-P}$ that was released consistently increased as immersion period became greater. Corn and wheat residue either accumulated or released $\text{NO}_3\text{-N}$ depending on residue collection date. Soybean residue accumulated an average of $20 \mu\text{g NO}_3\text{-N g}^{-1}$ residue. Wheat residue obtained on five of the collection dates accumulated an average of $13 \mu\text{g NO}_3\text{-N g}^{-1}$ residue. Residue collection date

also influenced accumulation of $\text{NH}_4\text{-N}$ by soybean and wheat residue. Corn residue released an average of $77 \mu\text{g NH}_4\text{-N g}^{-1}$ residue. The type of crop residue material, the amount of time the residue has remained in the field following harvest, and residue immersion period were found to influence nutrient concentrations of solution.

Keywords Crop residue · Nitrogen movement · Nutrient losses · Phosphorus · Water quality

1 Introduction

Schreiber (1985) reported that crop residues on the soil surface subjected to rainfall were a significant source of soluble nutrients in agricultural runoff. The dissolved phosphorus (P) release from vegetation in warm climates is dominated by decomposition and mineralization (Noack et al. 2012; Damon et al. 2014). The amounts and patterns of nitrogen (N) mineralization from decomposing crop residues are affected by their initial chemical composition and condition, and by climatic variables (Kumar and Goh 2003; Rosolem et al. 2005). Accumulation (nutrient movement from solution into residue materials) and release (nutrient movement from the residue materials into solution) of nutrients by crop residue have been found to change with progressive decomposition of residue materials (Harvis and Alberts 1993). In cold climates, freeze-thaw cycles have been reported to increase water extractable phosphorus release from plants (Liu et al. 2019).

J. E. Gilley (✉)
USDA-ARS, Agroecosystem Management Research Unit,
University of Nebraska, Lincoln, NE 68583, USA
e-mail: john.gilley@usda.gov

D. B. Marx
Department of Statistics, University of Nebraska, Lincoln, NE
68583, USA

Schreiber and McDowell (1985) examined the effects of cumulative rainfall on release of N and P from wheat straw residues. Less than 1% of the total N and 8–14% of the total P in the wheat residue were released for the given experimental conditions. Release was found by Schreiber (1985) to increase as greater amounts of wheat residue were added. In a companion study, Schreiber (1999) found that less than 1.5% of the total N and 4.2–6.0% of the total P contained in corn residue were released. Lower rainfall intensities and higher residue loading rates generally produced greater nutrient concentrations and losses.

Cermak et al. (2004) conducted a laboratory study to measure accumulation and release of N and P from soybean, corn, and winter wheat residue collected from a farm in southeast Nebraska. At the time of collection, the soybean, corn, and winter wheat residue had been in the field following harvest for 16, 77, and 119 days, respectively. The crop residue materials were placed in solutions containing inorganic nutrients. An increase in initial solution concentration of $\text{PO}_4\text{-P}$ did not affect release of $\text{PO}_4\text{-P}$ from soybean and corn residue. However, the amount of $\text{PO}_4\text{-P}$ released from soybean and corn residue consistently increased as the amount of time residue remained in solution increased.

Cropland areas with tile drains are sometimes submerged for 24-h periods (ASAE Standards 1998). Likewise, storm runoff within terrace channels and basins may remain on-site for up to 48 h (ASAE Standards 1997). When crop residue materials are submerged for extended periods, there may be a potential for substantial accumulation or release of nutrients by crop residue. Lozier and Macrae (2017) found that ponding led to greater dissolved reactive phosphorus release from plant materials than rainfall.

Vegetative materials have been reported to influence the nutrient content of runoff (Miller et al. 1994; Elliot 2013). If the conditions under which crop residues accumulate and release nutrients can be identified, it may be possible to adopt cropping and management practices that reduce nutrient concentrations in runoff. Nutrients accumulated or released by residue materials could be maintained on-site and used by succeeding crops, rather than transported in runoff causing off-site water quality degradation.

Crop residue materials may be immersed for a relatively short time by overland flow or for extended periods when they are located within tile-drained areas, or terrace channels and basins. Therefore, the length of

time stalks was immersed in nutrient solutions was included as an experimental variable in this investigation. Decomposition may affect the ability of stalks to accumulate or release nutrients. Thus, stalks were collected for this study on six dates following harvest over an approximate 1-year period. The objective of this laboratory study was to measure accumulation and release of P and N by corn, soybean, and winter wheat residue collected on six dates following harvest over an approximate 1-year period.

2 Materials and Methods

2.1 Experimental Design

The experimental variables used in this study included three nutrient solutions into which the stalks were immersed ($\text{PO}_4\text{-P}$, $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$), three types of stalks (corn, soybean, and wheat), six dates following harvest on which stalks were collected, and five stalk immersion periods (25 s (0.42 min), 250 s (4.2 min), 2500 s (42 min), 25,000 s (6.9 h), and 86,400 s (24 h)). Four replications of each of the experimental treatments were examined for a total of 1080 individual tests. Immersion periods of 25,000 s (6.9 h) and 86,400 s (24 h) were included to characterize conditions where stalks are submerged for extended periods such as tile-drained areas or terrace channels and basins.

2.2 Site Description and Stalk Collection

The stalks were collected from three fields at the University of Nebraska Roger's Memorial Farm (40° 49' N, 96° 41' W) located 18 km east of Lincoln, Nebraska in Lancaster County. The silty clay loam soils at the site developed in loess under prairie vegetation. The farm was cropped using a corn, soybean, and winter wheat rotation, under a no-till management system. This region has a humid continental climate with winters that are cold but relatively dry, and summers that are hot and humid (Fig. 1). Mean annual precipitation is 711 mm and is concentrated in the summer months.

Anhydrous ammonia was applied to the corn acreage at a rate of 140 kg N ha⁻¹ and ammonium nitrate was added to the wheat acreage at a rate of 140 kg N ha⁻¹. No commercial fertilizer was applied to the soybean acreage. Corn residue was collected 0, 28, 61, 142, 240, and 349 days following harvest, soybean residue

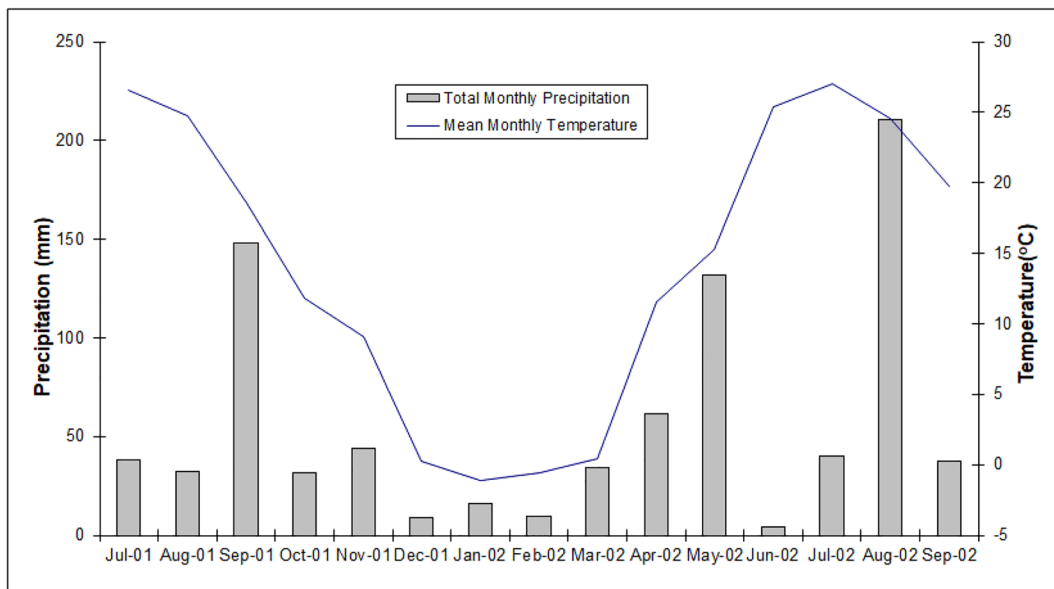


Fig. 1 Total monthly precipitation and mean monthly temperature from July 2001 to September 2002 at the site where residue was collected

was obtained 2, 30, 63, 144, 242, and 351 days after harvest, and wheat residue was collected 0, 31, 58, 119, 228, and 365 days following harvest.

The residue materials were collected at selected intervals for approximately 1 year following harvest. A subsequent crop was grown at each of the fields where residue materials were obtained and residue collection was terminated before the next harvest. Since a crop rotation was used at the farm, it was not difficult to distinguish the residue materials of interest from crops grown during previous years.

Soil was removed from the stalks and they were cut into sections approximately 11 cm long and placed in an oven maintained at a temperature of 60 °C for 48 h. The dried stalks were then stored in plastic bags for later use in the laboratory tests. The same mass of stalks was used in each of the laboratory tests conducted on a given type of crop residue.

2.3 Nutrient Concentration of Stalks

Procedures described by Harvis and Alberts (1993) were used to measure P and N concentrations of subsamples of the stalks prior to immersion. The stalks were dried at 60 °C for 2 h, and a 1-g sample was placed in a test tube containing 30 mL of deionized-distilled water and shaken for 2 h. After the liquid extraction process, the sample was centrifuged and filtered before P and N analyses were performed. The solutions were then

analyzed for PO₄-P (Murphy and Riley 1962), NO₃-N, and NH₄-N (Lachat, Zellweger Analytics, Milwaukee, WI). The nutrient concentrations of the stalks prior to immersion for each of the residue collection dates are shown in Table 1. The laboratory analyses provided information on the extractable nutrients rather than the total nutrients contained in the residue materials. Information on extractable nutrient content of the crop residue was helpful when examining the experimental results from the laboratory immersions.

2.4 Nutrient Concentration of Solutions

The laboratory procedures were established to replicate conditions existing in the field when a unit volume of stalk material is immersed by overland flow. The stalk diameter of corn, soybean, and wheat has been reported as 2.38, 0.60, and 0.29 cm, and their density is 168, 258, and 148 kg m³, respectively (Gilley et al. 1994). Thus, the volume provided by a unit mass of stalks varies among residue materials.

One-liter wide-mouth glass jars were used for the laboratory tests. The quantity of stalks required to fill the test volume was first determined (25, 35, and 50 g for wheat, soybean, and corn stalks, respectively). The selected stalk volume provided enough space above the vegetative materials to allow for complete immersion after the stalks absorbed water. The quantity of water

Table 1 Extractable nutrient content of corn, soybean, and wheat stalks as affected by time since harvest

Corn			
Time since harvest (days)	PO ₄ -P ^[a] (μg of nutrient g ⁻¹ residue)	NO ₃ -N (μg of nutrient g ⁻¹ residue)	NH ₄ -N (μg of nutrient g ⁻¹ residue)
0 ^[b]	328a	1428b	280a
28	620a	168a	405ab
61	530a	67a	700b
142	385a	102a	194a
240	307a	51a	83a
349	229a	12a	38a
Soybean			
Time since harvest (days)	PO ₄ -P (μg of nutrient g ⁻¹ residue)	NO ₃ -N (μg of nutrient g ⁻¹ residue)	NH ₄ -N (μg of nutrient g ⁻¹ residue)
2	153a	19b	58a
30	211a	8a	85a
63	178a	4a	43a
144	167a	6a	41a
242	192a	5a	30a
351	126a	2a	27a
Wheat			
Time since harvest (days)	PO ₄ -P (μg of nutrient g ⁻¹ residue)	NO ₃ -N (μg of nutrient g ⁻¹ residue)	NH ₄ -N (μg of nutrient g ⁻¹ residue)
0	418b	402b	55ab
31	178a	35a	49ab
58	106a	65a	24a
119	143a	38a	100c
228	159a	20a	88bc
365	103a	3a	57ab

^[a]The reported measurements were obtained using laboratory procedures developed by Harvis and Alberts (1993). Each of the reported nutrient content values is the mean of two measurements

^[b]For a given residue material, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test

necessary to immerse the stalks was then identified (630 mL for corn, and 840 mL for soybean and wheat).

The initial solution concentration of the PO₄-P, NO₃-N, and NH₄-N constituents used in this study was 6 μg mL⁻¹. This concentration was selected after reviewing results from a field runoff study reported by Nicolaisen et al. (2007). Nicolaisen et al. (2007) measured runoff nutrient contents from plots on which beef cattle or swine manure was added at rates required to meet annual corn N requirements. Concentrations of

total P in runoff from the plots containing residue and manure were approximately 6 μg mL⁻¹.

Inorganic sources for PO₄-P, NO₃-N, and NH₄-N were American Chemical Society certified K₂HPO₄, KNO₃, and NH₄Cl. The inorganic salts were added to deionized-distilled water to obtain the desired nutrient concentrations and samples of the solutions were analyzed for PO₄-P, NO₃-N, and NH₄-N. The stalks were placed in each jar, and the nutrient solution was added until the stalks were completely immersed. The jars were left undisturbed at room temperature for the designated immersion period and were covered to reduce evaporation.

The stalks were removed once the designated contact time had been reached. The remaining nutrient solution was then filtered through a 0.45-μm filter and stored in a cooler at 1 °C for later analysis. Each solution was analyzed for PO₄-P (Murphy and Riley 1962), NO₃-N, and NH₄-N (Lachat, Zellweger Analytics, Milwaukee, WI). To normalize data, results were reported as the mass of nutrient accumulated or released per unit mass of stalk material.

2.5 Statistical Analyses

The least significant difference (LSD) test was used to evaluate the effects of time since harvest on extractable nutrient content of each of the corn, soybean, and wheat stalks prior to immersion (Table 1). A probability level $p \leq 0.05$ was considered significant. Separate statistical analyses were performed for measurements obtained on each of the stalk materials immersed in nutrient solutions (Tables 2, 3, and 4). Time since harvest and immersion period were treatment factors used in the statistical analyses. Initial statistical tests indicated that standard analysis of variance (ANOVA) procedures could be employed (Steel and Torri 1980). ANOVA was performed to determine the effects of the treatment factors on changes in nutrient content of solution (SAS 2003). If a significant difference was identified, the LSD test was used to determine differences among experimental treatments. A probability level $p \leq 0.05$ was again considered significant.

3 Results

Changes in the PO₄-P, NO₃-N, and NH₄-N content of solutions were significantly influenced by time since

Table 2 Change in PO₄-P content of solution as affected by time since harvest and immersion period for selected crop residue materials

	Change in PO ₄ -P content ^[a] (μg of PO ₄ -P g ⁻¹ residue)		
	Corn	Soybean	Wheat
Time since harvest ^[b] (d)			
Com 0; soybean 2; wheat 0	100b ^[c]	97e	152e
Com 28; soybean 30; wheat 31	152c	42d	22ab
Com 61; soybean 63; wheat 58	180d	35c	32b
Com 142; soybean 144; wheat 119	181d	45d	81c
Com 240; soybean 242; wheat 228	149c	23b	114d
Com 349; soybean 351; wheat 365	82a	0a	12a
Immersion period ^[d]			
25 s (0.42 min)	14a	2a	5a
250 s (4.2 min)	18a	17b	23b
2500 s (42 min)	41b	24b	47c
25,000 s (6.9 h)	220c	61c	111d
86,400 s (24 h)	411d	97d	157e
ANOVA (Pr > F)			
Time since harvest	0.01	0.01	0.01
Immersion period	0.01	0.01	0.01
Time since harvest × immersion period	0.01	0.01	0.01

^[a] The change in PO₄-P content of solution was obtained by subtracting the final solution concentration from the initial concentration, multiplying the difference by the volume of solution, and dividing the result by the residue mass. Therefore, positive changes in PO₄-P content indicate release, while negative values represent accumulation

^[b] For each time since harvest, reported changes in PO₄-P content of solution are the mean of 20 measurements

^[c] For a given time since harvest and immersion period, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test

^[d] For each immersion period, reported changes in PO₄-P content of solution are the mean of 24 measurements

harvest and immersion period for each of the crop residue materials (Tables 2, 3, and 4). A significant interaction between time since harvest and stalk immersion period was found for each of the nutrient constituents. Graphs showing interactive effects for the six collection dates and five immersion periods were cumbersome and difficult to interpret. Therefore, the presentation below focuses on the effects of time since harvest and immersion period on changes in nutrient concentrations.

3.1 Release of PO₄-P by Crop Residue Materials

3.1.1 Release of PO₄-P by Corn Stalks

No significant differences in extractable PO₄-P content of corn stalks were found among residue collection dates and the mean value was 400 μg of PO₄-P extracted

g⁻¹ residue (Table 1). However, significant differences in the quantity of PO₄-P that was released from corn stalks were found among residue collection dates (Table 2). Release of PO₄-P varied from 82 to 181 μg g⁻¹ residue for corn stalks collected 349 and 142 days following harvest, respectively. The smallest PO₄-P release occurred for corn stalks collected 349 days following harvest which corresponded with the lowest measured extractable nutrient content.

As time of immersion increased from 25 s (0.42 min) to 86,400 s (24 h), the quantity of PO₄-P released by corn stalks increased from 14 to 411 μg g⁻¹ residue (Table 2; Fig. 2). Cermak et al. (2004) also reported that corn residue consistently released more PO₄-P as residue immersion period became greater, with the greatest PO₄-P loss occurring 86,400 s (24 h) after immersion.

The mean 400 μg PO₄-P g⁻¹ residue contained in the corn stalks is similar to the 411 μg PO₄-P g⁻¹ residue

Table 3 Change in NO₃-N content of solution as affected by time since harvest and immersion period for selected crop residue materials

	Change in NO ₃ -N content ^[a] (μg of nutrient g ⁻¹ residue)		
	Corn	Soybean	Wheat
Time since harvest ^[b] (days)			
Com 0; soybean 2; wheat 0	212b ^[c]	-20b	444b
Com 28; soybean 30; wheat 31	177b	-30a	-16a
Com 61; soybean 63; wheat 58	32a	-23b	-19a
Com 142; soybean 144; wheat 119	8a	-8c	-10a
Com 240; soybean 242; wheat 228	-3a	-17b	-3a
Com 349; soybean 351; wheat 365	-16a	-19b	-15a
Immersion period ^[d]			
25 s (0.42 min)	5a	-5b	9a
250 s (4.2 min)	10a	-2b	1a
2500 s (42 min)	41a	-1b	79b
25,000 s (6.9 h)	109c	-5b	110b
86,400 s (24 h)	175d	-84a	106b
ANOVA (Pr > F)			
Time since harvest	0.01	0.01	0.01
Immersion period	0.01	0.01	0.01
Time since harvest × immersion period	0.01	0.01	0.01

^[a] The change in NO₃-N content of solution was obtained by subtracting the final solution concentration from the initial concentration, multiplying the difference by the volume of solution, and dividing the result by the residue mass. Therefore, positive changes in NO₃-N indicate release, while negative values represent accumulation

^[b] For a given time since harvest, reported changes in NO₃-N content of solution are the mean of 20 measurements

^[c] For a given time since harvest and immersion period, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test

^[d] For each immersion period, reported changes in NO₃-N content of solution are the mean of 24 measurements

released during the 86,400-s (24 h) immersion period. Thus, most of the PO₄-P contained in the corn stalks appears to have been released in 24 h. Ginting et al. (1998) reported that corn released nearly all P after 72,000 s (20 h) of surface ponding.

3.1.2 Release of PO₄-P by Soybean Stalks

The extractable PO₄-P content of soybean stalks did not vary significantly among residue collection dates and the mean value was 171 μg PO₄-P g⁻¹ residue (Table 1). Changes in the PO₄-P content of solutions in which soybean stalks were immersed varied significantly among collection dates ranging from 0 μg g⁻¹ residue for residue collected 351 days after harvest to 97 μg g⁻¹ residue for residue obtained 2 days following harvest (Table 2). The quantity of PO₄-P released from the soybean stalks during the final two residue collection

periods was significantly less than the values released during the other intervals.

Residue immersion period also significantly influenced release of PO₄-P by soybean stalks. As immersion period increased from 25 s (0.42 min) to 86,400 s (24 h), the mean amount of PO₄-P released from soybean stalks consistently increased from 2 to 97 μg g⁻¹ residue (Table 2; Fig. 3). Cermak et al. (2004) also found that soybean residue consistently released more PO₄-P as residue immersion period increased. The 97 μg PO₄-P g⁻¹ residue released from the soybean stalks during the 86,400-s (24 h) immersion period was 57% of the mean 171 μg PO₄-P g⁻¹ residue contained in the soybean stalks.

3.1.3 Release of PO₄-P by Wheat Stalks

The extractable PO₄-P content of wheat stalks at harvest was 418 μg g⁻¹ residue which was significantly larger

Table 4 Change in $\text{NH}_4\text{-N}$ content of solution as affected by time since harvest and immersion period for selected crop residue materials

	Change in $\text{NH}_4\text{-N}$ content ^[a] (μg of nutrient g^{-1} residue)		
	Corn	Soybean	Wheat
Time since harvest ^[b] (days)			
Com 0; soybean 2; wheat 0	80c ^[c]	7d	11c
Com 28; soybean 30; wheat 31	154d	- 11c	- 64a
Com 61; soybean 63; wheat 58	124d	- 47ab	- 52a
Com 142; soybean 144; wheat 119	41b	- 43b	- 7b
Com 240; soybean 242; wheat 228	54bc	- 17c	22c
Com 349; soybean 351; wheat 365	8a	- 55a	201d
Immersion period ^[d]			
25 s (0.42 min)	- 9a	- 35ab	- 30a
250 s (4.2 min)	- 5a	- 34ab	- 23a
2500 s (42 min)	2a	- 37a	- 21a
25,000 s (6.9 h)	131b	- 26b	57b
86,400 s (24 h)	264c	- 5c	110c
ANOVA ($\text{Pr} > F$)			
Time since harvest	0.01	0.01	0.01
Immersion period	0.01	0.01	0.01
Time since harvest \times immersion period	0.01	0.01	0.01

^[a] The change in $\text{NH}_4\text{-N}$ content of solution was obtained by subtracting the final solution concentration from the initial concentration, multiplying the difference by the volume of solution, and dividing the result by the residue mass. Therefore, positive changes in nutrient content indicate release, while negative values represent accumulation

^[b] For a given time since harvest, reported changes in $\text{NH}_4\text{-N}$ content of solution are the mean of 20 measurements

^[c] For a given time since harvest and immersion period, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test

^[d] For each immersion period, reported changes in $\text{NH}_4\text{-N}$ content of solution are the mean of 24 measurements

than values obtained at the other collection periods (Table 1). No significant differences in extractable $\text{PO}_4\text{-P}$ content were found among the other residue collection dates. Lozier et al. (2017) reported that water extractable P concentrations in wheat residue collected in a cool temperate region did not change during the non-growing season.

Wheat stalks collected on day 0 released $152 \mu\text{g PO}_4\text{-P g}^{-1}$ residue which was significantly greater than the other collection dates (Table 2). Release of $\text{PO}_4\text{-P}$ for the other collection dates varied from $12 \mu\text{g PO}_4\text{-P g}^{-1}$ residue for wheat stalks collected 365 days after harvest to $114 \mu\text{g PO}_4\text{-P g}^{-1}$ residue for wheat stalks obtained 228 days following harvest. Release of $\text{PO}_4\text{-P}$ from wheat stalks consistently increased from 5 to $157 \mu\text{g g}^{-1}$ residue as residue immersion period increased from 25 s (0.42 min) to 86,400 s (24 h).

The mean $185 \mu\text{g PO}_4\text{-P g}^{-1}$ residue contained in the wheat stalks is slightly larger than the $157 \mu\text{g PO}_4\text{-P g}^{-1}$ residue released from the wheat stalks during the 86,400-s (24 h) immersion period. Thus, most of the $\text{PO}_4\text{-P}$ contained in the wheat stalks appears to have been released in 24 h.

3.2 Release and Accumulation of $\text{NO}_3\text{-N}$ by Crop Residue Materials

3.2.1 Release of $\text{NO}_3\text{-N}$ by Corn Stalks

The extractable $\text{NO}_3\text{-N}$ content of corn stalks varied from a high of 1428 to a low of $12 \mu\text{g g}^{-1}$ residue as time since harvest increased from 0 to 349 days (Table 1). The $1428 \mu\text{g g}^{-1}$ residue of extractable $\text{NO}_3\text{-N}$ obtained for corn stalks collected at harvest was significantly larger than values obtained on the other collection dates. No

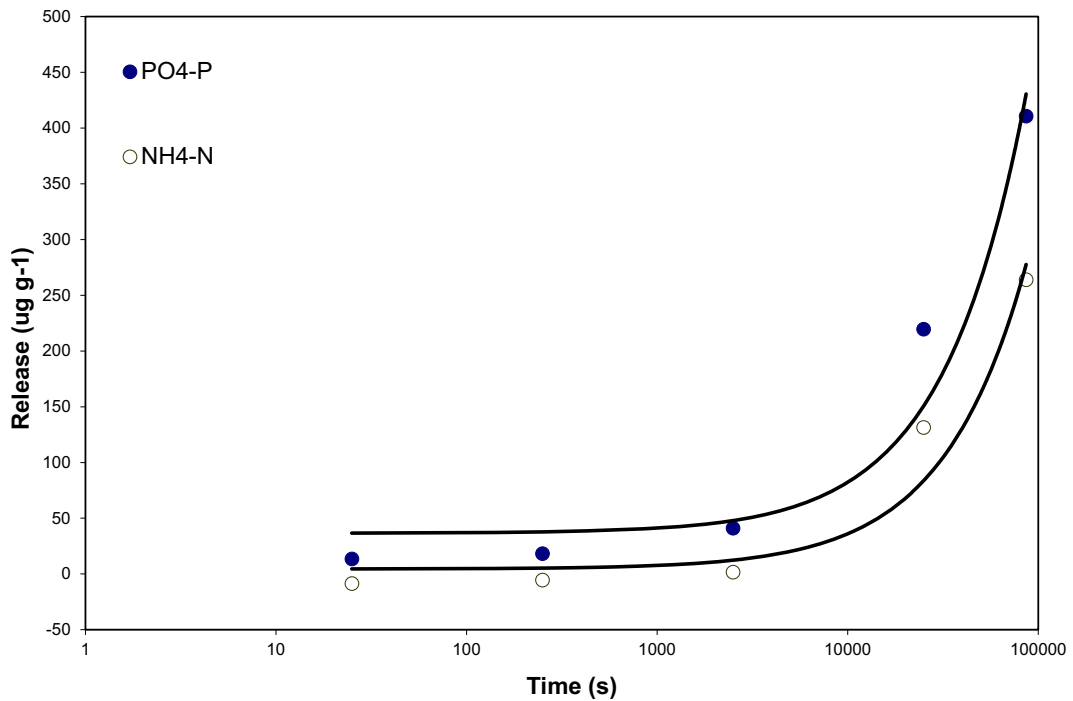


Fig. 2 Release of PO₄-P and NH₄-N from corn stalks as affected by immersion period

significant differences in extractable NO₃-N content were found among the other residue collection dates.

Residue collection date significantly affected release of NO₃-N by corn stalks with values decreasing from 212 to

32 μg g⁻¹ residue as the collection period following harvest increased from 0 to 61 days (Table 3). Changes in NO₃-N content of solutions containing corn stalks collected 142, 240, and 349 days following harvest were

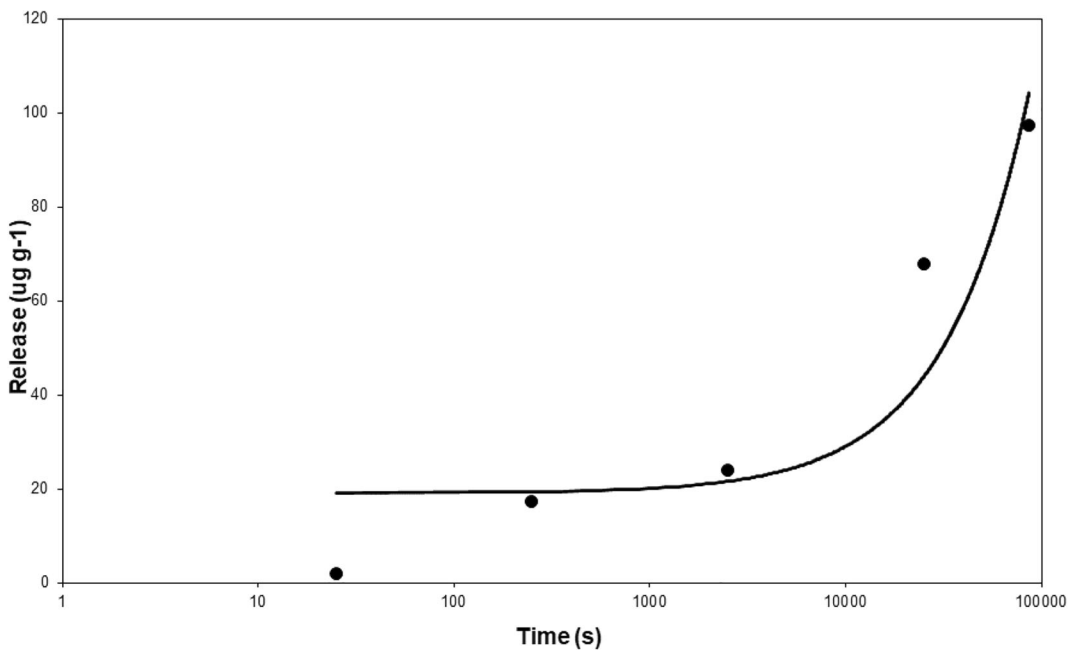


Fig. 3 Release of PO₄-P from soybean stalks as affected by immersion period

minimal. Release of $\text{NO}_3\text{-N}$ by corn stalks varied significantly among immersion periods. The amount of $\text{NO}_3\text{-N}$ released consistently increased from 5 to $175 \mu\text{g g}^{-1}$ residue as immersion period increased from 25 s (0.42 min) to 86,400 s (24 h). Cermak et al. (2004) found that as residue immersion period increased, corn residue released $\text{NO}_3\text{-N}$ at rates ranging from 7 to $55 \mu\text{g g}^{-1}$ residue. The corn residue used by Cermak et al. (2004) contained $163 \mu\text{g}$ of water extractable $\text{NO}_3\text{-N g}^{-1}$ residue while the corn residue used in the present investigation contained an average of $305 \mu\text{g NO}_3\text{-N g}^{-1}$ residue.

3.2.2 Accumulation of $\text{NO}_3\text{-N}$ by Soybean Stalks

The extractable $\text{NO}_3\text{-N}$ content of soybean stalks varied from a high of 19 to a low of $2 \mu\text{g g}^{-1}$ residue as time since harvest increased from 2 to 351 days (Table 1). The $19 \mu\text{g g}^{-1}$ residue of extractable $\text{NO}_3\text{-N}$ obtained for soybean stalks collected 2 days following harvest was substantially larger than values obtained on the other collection dates. No significant differences in extractable $\text{NO}_3\text{-N}$ content were found among the residue collection dates varying from 30 to 351 days after harvest.

Accumulation of $\text{NO}_3\text{-N}$ by soybean stalks varied significantly among residue collection dates varying from $8 \mu\text{g NO}_3\text{-N g}^{-1}$ residue for soybean stalks collected 144 days after harvest to $30 \mu\text{g NO}_3\text{-N g}^{-1}$ residue for the 30-day collection period (Table 3). Immersion period also significantly affected accumulation by soybean stalks. The largest amount of $\text{NO}_3\text{-N}$ accumulated by soybean stalks was $84 \mu\text{g NO}_3\text{-N g}^{-1}$ residue which occurred after an immersion period of 86,400 s (24 h) (Table 3; Fig. 4). Changes in $\text{NO}_3\text{-N}$ content of solution were minimal for the other soybean immersion periods.

3.2.3 Accumulation and Release of $\text{NO}_3\text{-N}$ by Wheat Stalks

The $402 \mu\text{g g}^{-1}$ residue of extractable $\text{NO}_3\text{-N}$ in wheat stalks collected on day 0 was significantly larger than values obtained on the other residue collection dates (Table 1). No significant differences in extractable $\text{NO}_3\text{-N}$ content of the wheat stalks were measured for the other collection dates.

The wheat stalks obtained on day 0 released $444 \mu\text{g NO}_3\text{-N g}^{-1}$ residue which was possible because of the relatively large amount of extractable $\text{NO}_3\text{-N}$ contained in the wheat stalks at harvest (Table 3). However, a

mean value of $13 \mu\text{g NO}_3\text{-N g}^{-1}$ residue was accumulated by wheat stalks on the other five collection dates and the accumulation is assumed to be biologically driven. Significant differences in the amounts of $\text{NO}_3\text{-N}$ that were released were found among immersion periods with values varying from $1 \mu\text{g NO}_3\text{-N g}^{-1}$ residue for the 250 s (4.2 min) immersion period to $110 \mu\text{g NO}_3\text{-N g}^{-1}$ residue for the 25,000 s (6.9 h) immersion period.

The mean $94 \mu\text{g NO}_3\text{-N g}^{-1}$ residue contained in the wheat stalks is similar to the $106 \mu\text{g NO}_3\text{-N g}^{-1}$ residue released from wheat stalks during the 86,400 s (24 h) immersion period. Thus, most of the $\text{NO}_3\text{-N}$ contained in the wheat stalks appears to have been released in 24 h.

3.3 Accumulation and Release of $\text{NH}_4\text{-N}$ by Crop Residue Materials

3.3.1 Release of $\text{NH}_4\text{-N}$ by Corn Stalks

The extractable $\text{NH}_4\text{-N}$ content of corn stalks varied significantly among collection dates varying from $38 \mu\text{g NH}_4\text{-N g}^{-1}$ residue at 349 days following harvest to $700 \mu\text{g NH}_4\text{-N g}^{-1}$ residue at 61 days after harvest (Table 1). Release of $\text{NH}_4\text{-N}$ by corn stalks also varied significantly among collection dates ranging from $8 \mu\text{g NH}_4\text{-N g}^{-1}$ residue at 349 days following harvest to $154 \mu\text{g NH}_4\text{-N g}^{-1}$ residue at 28 days after harvest (Table 4). Changes in $\text{NH}_4\text{-N}$ content of solutions in which corn stalks were immersed for 25 s (0.42 min) to 2500 s (42 min) were minimal (Fig. 2). However, 131 and $264 \mu\text{g NH}_4\text{-N g}^{-1}$ residues were released for immersion periods of 25,000 s (6.9 h) and 86,400 s (24 h), respectively.

The mean extractable $\text{NH}_4\text{-N}$ content of corn stalks was $283 \mu\text{g NH}_4\text{-N g}^{-1}$ residue (Table 1). This value is slightly larger than the $264 \mu\text{g NH}_4\text{-N g}^{-1}$ residue released from corn stalks during the 24 h immersion period. Thus, most of the extractable $\text{NH}_4\text{-N}$ content of the corn stalks was released for residue immersed for 24 h.

3.3.2 Accumulation and Release of $\text{NH}_4\text{-N}$ by Soybean Stalks

The extractable $\text{NH}_4\text{-N}$ content of soybean stalks did not vary significantly among residue collection dates and the mean value was $47 \mu\text{g NH}_4\text{-N g}^{-1}$ residue (Table 1). The change in $\text{NH}_4\text{-N}$ concentration for soybean stalks

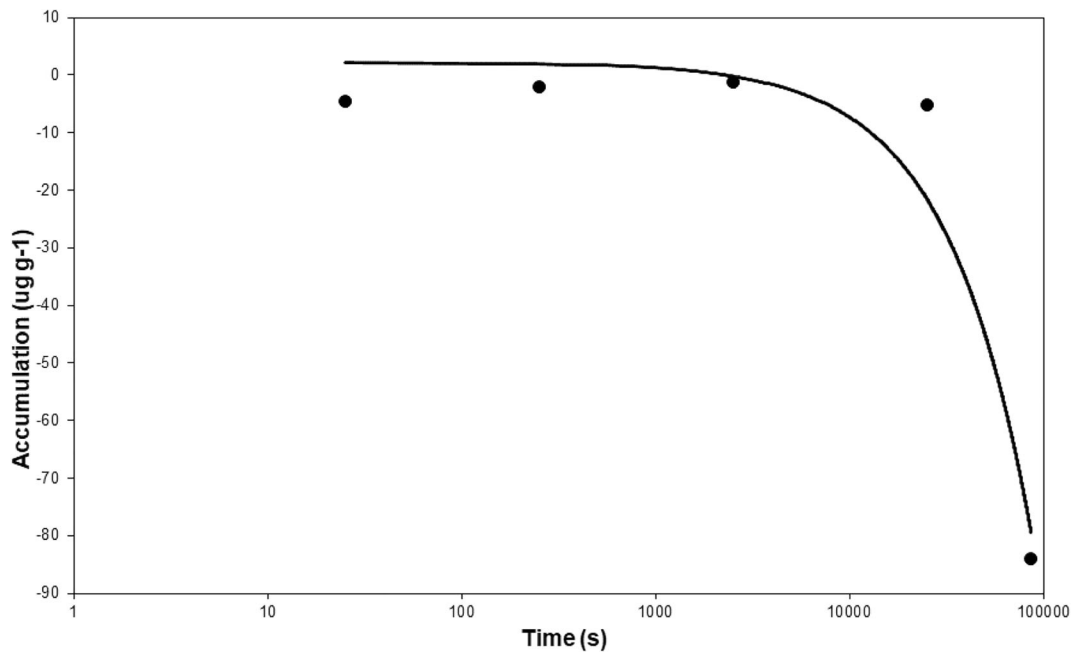


Fig. 4 Accumulation of NO₃-N by soybean stalks as affected by immersion period

collected 2 and 30 days following harvest was minimal (Table 4). However, accumulation of NH₄-N occurred for the other collection dates with values varying from 17 µg g⁻¹ residue for residue collected 242 days after harvest to 55 µg g⁻¹ residue for residue obtained 351 days following harvest. The length of time soybean stalks was immersed also significantly affected accumulation of NH₄-N. Accumulation of NH₄-N by soybean stalks varied from 5 µg g⁻¹ residue 86,400 s (24 h) following immersion to 37 µg g⁻¹ residue 2500 s (0.42 min) after immersion.

3.3.3 Accumulation and Release of NH₄-N by Wheat Stalks

The extractable NH₄-N content of wheat stalks varied significantly among collection dates with values ranging from 24 µg NH₄-N g⁻¹ residue for residue collected 58 days following harvest to 100 µg NH₄-N g⁻¹ residue for residue obtained 119 days after harvest (Table 1). The wheat stalks released or accumulated NH₄-N depending on residue collection date (Table 4). The wheat stalks accumulated 64 µg NH₄-N g⁻¹ residue for the residue collected 31 days following harvest. In contrast, 201 µg NH₄-N g⁻¹ residue was released by wheat stalks collected 365 days after harvest.

Accumulation or release of nutrients in wheat residue was also influenced by immersion period. An average of 25 µg NH₄-N g⁻¹ residue was accumulated for immersion periods of 25 s (0.42 min), 250 s (4.2 min), and 2500 s (42 min). In comparison, 110 µg NH₄-N g⁻¹ residue was released for an immersion period of 86,400 s (24 h). Cermak et al. (2004) found that the wheat residue used in their study accumulated an average of 35 µg NH₄-N g⁻¹ residue for residue immersion periods varying from 25 s (0.42 min) to 2500 s (42 min).

4 Discussion

4.1 Environmental Implications of Nutrient Release

Eghball et al. (2000) conducted a rainfall simulation study on a no-till site near Council Bluffs, Iowa with a corn residue cover of 79%. A residue mass of approximately 3.9×10^3 kg ha⁻¹ was estimated for this location (Gregory 1982). In the present study, corn residue released an average of 41 µg PO₄-P g⁻¹ residue over a 42 min period. Therefore, approximately 0.16 kg ha⁻¹ of PO₄-P could be released over a 42 min period on a site with a corn residue cover of 79%. During the second rainfall simulation run, Eghball et al. (2000) measured a total PO₄-P load of 0.31 kg ha⁻¹ over a 60-min period on

plots without a grass hedge where beef cattle manure had been applied at a rate required to meet annual corn N requirements. Thus, the quantity of $\text{PO}_4\text{-P}$ released from the corn residue collected in this study appears to be about half of the amount measured in runoff over a 60 min period in the study conducted by Eghball et al. (2000).

Eghball and Gilley (1999) conducted a rainfall simulation study on a no-till site near Lincoln, Nebraska that had a wheat residue cover of 65%. A wheat residue mass of approximately $2.1 \times 10^3 \text{ kg ha}^{-1}$ was estimated for the study site using equations presented by Gregory (1982). Wheat residue released an average of $47 \mu\text{g PO}_4\text{-P g}^{-1}$ residue over a 42 min period in the present study. Therefore, approximately 0.10 kg ha^{-1} of $\text{PO}_4\text{-P}$ could be released over a 42 min period on a site with a wheat residue cover of 65%. For wheat plots on which beef cattle manure was recently applied at a rate required to meet annual corn N requirements, Eghball and Gilley (1999) measured a total $\text{PO}_4\text{-P}$ load of 0.29 kg ha^{-1} over a 60 min period during the second rainfall simulation run. Thus, using values obtained in this investigation, wheat residue appears to have the potential to supply about a third of the $\text{PO}_4\text{-P}$ measured in runoff over a 60 min period in the study reported by Eghball and Gilley (1999).

4.2 Agronomic Implications of Nutrient Release

A corn residue mass of approximately $3.9 \times 10^3 \text{ kg ha}^{-1}$ was estimated (Gregory 1982) for the no-till site near Council Bluffs, Iowa where Eghball et al. (2000) conducted their rainfall simulation study. The $\text{NO}_3\text{-N}$ content of corn residue at the time of harvest was found in the present investigation to be $1428 \mu\text{g of NO}_3\text{-N g}^{-1}$ residue (Table 1). Thus, if all the N in corn residue was released, there would be $5.57 \text{ kg N ha}^{-1}$ available or approximately 0.83% of the 151 kg N ha^{-1} required for a corn crop with a target yield of 9.4 Mg ha^{-1} .

The largest amount of $\text{PO}_4\text{-P}$ measured in corn residue in the present study was $620 \mu\text{g of PO}_4\text{-P g}^{-1}$ residue (Table 1). Thus, the total amount of P contained in corn residue at the site examined by Eghball et al. (2000) was $0.790 \text{ kg N ha}^{-1}$. This value represents 3.1% of the 151 kg P ha^{-1} needed by a corn crop with a target yield of 9.4 Mg ha^{-1} . Thus, the N and P contained in the corn stalks would only provide a small percentage of the crop nutrient requirements of a succeeding corn crop.

4.3 Mechanisms Influencing Accumulation and Release of Nutrients

Crop residues have been reported to contain primarily inorganic P (McLaughlin et al. 1988). Therefore, release of mineral P may occur without microbial activity. The primary factor determining whether P will be mineralized as a result of residue decomposition is the P content of the crop residue. The P concentrations of crop residues are influenced by environmental, climatic, and soil conditions. In general, P will be mineralized if the P concentration in residues is greater than 3 mg g^{-1} ; immobilization will occur if the P concentration is less than 3 mg g^{-1} (Damon et al. 2014). The crop residues examined in this investigation each had a P content that was less than 3 mg g^{-1} so it can be assumed that P in the residue materials had been immobilized.

Vegetation has the potential to be a significant source of P to runoff following rainfall (Lozier and Macrae 2017). The release of nutrients from vegetation is dependent on crop species and climatic conditions. The number and timing of freeze-thaw cycles to which the vegetation has been exposed over the non-growing season can enhance P release (Elliott 2013; Riddle and Bergstrom 2013).

Havis and Alberts (1993) measured the mean nutrient mass released from corn and soybean residue during 1 h simulated rainfall experiments. The crop residue was obtained during seven different decomposition durations following harvest. The mean mass of nutrient released from corn and soybean residue was 46 and $29 \mu\text{g of PO}_4\text{-P g}^{-1}$ residue, respectively. In the present study, the mean amount of nutrient released from corn and soybean residue during a 42 min immersion period was 41 and $24 \mu\text{g of PO}_4\text{-P g}^{-1}$ of residue, respectively. Therefore, chemical dissolution appears to be the mechanism influencing the release of $\text{PO}_4\text{-P}$ from crop residue materials examined in this investigation.

In contrast to P, most of the N in crop residues is organic. Thus, microbial decomposition is primarily responsible for the release of mineral N from crop residues (Noack et al. 2012). Since it involves microbiological transformations, the release of N from residue materials is more dynamic and complex than P release.

Contact between ponded water and vegetation may provide a greater opportunity for nutrient mobilization than would occur under rainfall conditions. The

presence of standing or flowing water which most frequently occurs in the lower portions of a field, or within tile-drained areas and terrace channels and basins, may enhance accumulation or release of nutrients. Ginting et al. (1998) examined the release of P from corn residue as affected by the length of time residue remained in water. Approximately 34% of the total P in residue was released over a 5 min immersion period compared with 57% over a 20 h period.

4.4 Limitations of Laboratory Results

The amount of leafy material present on cropland areas varies substantially over time, rapidly decreasing following harvest. To provide relative uniformity among experimental treatments, all vegetative materials removed from the soil surface except the stalks were discarded in the present laboratory investigation. It was critical that the stalks for a given type of vegetation used in the laboratory tests were similar and relatively uniform. Only the stalks that were not crushed or damaged during harvest were selected for testing. Therefore, the laboratory results reported for stalks may not fully represent the accumulation and release of nutrients from all crop residue materials occurring under field conditions.

Drying of the residue materials in an oven resulted in a water content that was less than would have existed in the field. As a result, a greater quantity of water was adsorbed by the residue materials when they were immersed in solution in the laboratory than would have occurred under field conditions. Therefore, there was also an increased opportunity for the dried residue materials to release or accumulate nutrients.

The quantity of nutrients accumulated by crop residue materials during the growing season and at harvest is influenced by antecedent soil nutrient content, the amounts and timing of fertilizer applications, farm cropping and management conditions, climatic variables, and other factors. Similarly, the extractable nutrient content of residue materials following harvest is substantially impacted by climatic conditions which can be highly variable at a specific site. Therefore, the reported measurements of accumulation and release of crop residue materials in the present study are representative of a single geographic location during one period of time.

5 Conclusions

When averaged over all collection dates and contact times, the corn residue released $77 \mu\text{g NH}_4\text{-N g}^{-1}$ residue. The soybean and wheat residue either accumulated or released $\text{NH}_4\text{-N}$ depending on residue age. An average of $25 \mu\text{g NH}_4\text{-N g}^{-1}$ residue was accumulated by wheat residue for immersion periods of 25 s (0.42 min), 250 s (4.2 min), and 2500 s (42 min). The wheat residue released an average of $84 \mu\text{g NH}_4\text{-N g}^{-1}$ residue for immersion periods of 25,000 s (6.9 h) and 86,400 s (24 h).

Crop residue materials appear to have the potential to influence nutrient concentrations during immersion. Corn, soybean, and wheat residue materials release $\text{PO}_4\text{-P}$ during immersion, while soybean and wheat residue can accumulate $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in solution. The type of crop residue material, the amount of time the residue has remained in the field following harvest, and residue immersion period influence nutrient concentrations of solution.

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