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Leaching and Sorption of Nitrogen and Phosphorus by Crop Residue

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Abstract. *Overland flow from cropland areas often contains nutrients and residue materials can either contribute to runoff nutrient load through leaching or remove nutrients by sorption. Measurements were made of leaching and sorption of nitrogen and phosphorus from corn (Zea mays L.), soybean (Glycine max (L.) Merr.) and winter wheat (Triticum aestivum L. cv. Pastiche) residues placed in solutions containing inorganic nutrients. Variables used were type of residue material, nutrient constituent, solution concentration, and residue / solution contact time. For a given residue material and nutrient constituent, four different solution concentrations were used (PO_4-P: 0 to 16 μg mL^{-1}; NO_3-N and NH_4-N: 0 to 24 μg mL^{-1}), and changes in solution concentration over five selected residue / solution contact times (25 to 86400 sec) were measured. Soybean and wheat residue contained relatively small amounts of NO_3-N and therefore had minimal impact on the NO_3-N content of the solutions. An increase in initial solution concentration did not substantially affect PO_4-P leaching from corn and soybean residue but caused the amount of NH_4-N removed to decrease. As residue solution / contact time increased from 25 to 86400 s (1 day), the amount of PO_4-P leached from corn and soybean residue consistently increased. Wheat residue sorbed PO_4-P with an increase in sorption generally resulting from greater residue solution / contact time. Thus, crop residue materials appear to have the potential to influence the N and P content of runoff through leaching and sorption.*

Keywords. *Corn, Crop residue, Nutrients, Overland flow, Runoff, Soybeans, Water quality, Wheat.*

Runoff from cropland areas receiving manure or fertilizer may contribute to increased P and N delivery to streams and lakes. Important variables controlling P movement in surface runoff are transport (runoff and erosion) and source factors, such as manure or fertilizer application rate (Sharpley et al., 1993). The amount of P in runoff from a field may also depend on the concentration of soluble P in the soil (Pote et al., 1996). Phosphorus in fresh water systems is a limiting factor for eutrophication. Ammonium loss into surface waters can result in poisoning of aquatic organisms if NH_4-N concentrations are greater than 2.5 mg L^{-1} (USEPA, 1986). Nitrate in runoff from fields receiving manure, compost, or fertilizer may be carried into rivers and lakes. Elevated nitrate levels in the Gulf of Mexico contribute to the hypoxia zone, an area depleted of oxygen and marine life.

Schreiber and McDowell (1985) examined the effects of 25 mm of cumulative rainfall on leaching of N, P, and organic C from wheat straw residues. For a wheat straw loading rate of 4500 kg ha^{-1}, rainfall applied at selected intensities for durations varying from 15 to 218 min caused less than 1% of the total N and 8% to 14% of the total P in wheat residue to be leached. In a companion study, Schreiber (1985) found that nutrient leaching losses generally increased with larger wheat residue loading rates, while the percentage of nutrients removed from the wheat residue decreased. In another study, Schreiber (1999) found that less than 1.5% of the total N and 4.2% to 6.0% of the total P contained in corn residue were leached when 25 mm of rain was applied at a rate of 25 mm h^{-1}. Nutrient concentrations and losses were usually greater at lower rainfall intensities and higher residue loading rates.

Ginting et al. (1998) examined P leaching from corn stover as affected by the length of time the stover was placed in deionized-distilled water. Over a 5 min immersion period, 34% of the total P in stover was released compared to 57% over a 20 h period. Immersing corn stover in water (Ginting et al. 1998) caused greater nutrient leaching than exposing corn residue to simulated rainfall (Schreiber, 1999).

The focus of many of the previous studies has been on nutrient leaching from crop residue materials under simulated rainfall conditions. This investigation was conducted to evaluate the potential for crop residue materials to leach or sorb N or P under overland flow conditions where dissolved nutrients are contained in runoff. Small ponds can be created by crop residue during runoff events (Brenneman and Laflen, 1982). The cumulative volume generated by a large number of ponds can be substantial, even though the amount of water stored in individual ponds may be small (Gilley and Kottwitz, 1994). Cropland areas where tile drains are installed are sometimes submerged for 24 h periods (*ASAE Standards*, 1998). Storm runoff within terrace channels and basins may sometimes remain on-site for up to 48 h (*ASAE Standards*, 1997).

If the conditions under which crop residue materials leach and sorb nutrients can be identified, it may be possible to

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adopt cropping and management practices that reduce nutrient delivery by overland flow. Nutrients leached or sorbed by residue materials could be maintained on-site and used by the next crop, rather than transported in runoff causing off-site water quality degradation. The objective of this study was to measure leaching (nutrient movement from the residue materials into solution) and sorption (nutrient movement from solution into the residue materials) of N and P from corn, soybean, and winter wheat residue in solutions containing inorganic PO_4-P, NO_3-N, and NH_4-N.

MATERIALS AND METHODS

The experimental variables used in this study included type of crop residue (corn, soybean, and winter wheat), nutrient constituent (PO_4-P, NO_3-N, and NH_4-N), nutrient concentration (PO_4-P: 0, 4, 8, and 16 $\mu g\ mL^{-1}$; NO_3-N and NH_4-N: 0, 6, 12, and 24 $\mu g\ mL^{-1}$), and residue / solution contact time (25 s, 250 s (4.2 min), 2500 s (41.7 min), 25000 s (6.9 h), and 86400 s (1 day)). Four replications of each of the experimental treatments were examined for a total of 720 tests. Separate measurements were made for each solution concentration at each contact time. Residue / solution contact times of 25000 and 86400 s were included to characterize conditions where residue materials are submerged for extended periods such as tiled-drained areas or terrace channels and basins.

Residue materials were obtained from the Rogers Memorial Farm (40°49′ N, 96°41′ W) located near Lincoln, Nebraska. Inorganic fertilizer was applied to the crops grown at the site at rates required to reach yield goals without causing excessive soil nutrient accumulation. The corn (8.07 $Mg\ ha^{-1}$), soybean (2.71 $Mg\ ha^{-1}$), and winter wheat (2.52 $Mg\ ha^{-1}$) fields from which the residue was collected were harvested on September 14, September 26, and June 22, 2000, respectively. At the time of collection, corn (November 30, 2000), soybean (October 12, 2000), and winter wheat (October 19, 2000) residue materials had been in the field following harvest for 77, 16, and 119 days, respectively. The leaching and sorption measurements obtained in this study for a selected residue material are representative of conditions existing in a particular field at one point in time. As crop residue materials progressively decompose, their leaching and sorption characteristics are expected to change (Havis and Alberts, 1993).

To provide relative uniformity between experimental treatments, all vegetative materials except the stalks were discarded. Stalks 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 sealed plastic bags for later use in the laboratory tests.

One-liter wide-mouth glass jars were used for the tests. The amount of vegetative material required to fit within a glass jar was first identified. Since the vegetative materials can sorb a significant amount of water, a sufficient amount of space was provided above the vegetative materials to allow for complete immersion. Corn, soybean, and winter wheat residue were added at rates of 50, 35, and 25 g per jar, respectively, the amounts required to provide approximately the same residue volume in each jar.

K_2HPO_4, KNO_3, and NH_4Cl served as the inorganic sources for PO_4-P, NO_3-N, and NH_4-N, respectively. These inorganic salts were added to deionized-distilled water to obtain the desired nutrient concentrations. The vegetative materials were placed in each jar, and the nutrient solution was added until the residue materials were completely immersed. Immersion of the corn residue required 630 mL of solution, while 840 mL of solution was added to the jars containing soybean and winter wheat residue.

The jars were left undisturbed at room temperature for the designated residue / solution contact time and were covered to keep the vegetative materials in contact with the nutrient solution and prevent evaporation. Once the designated contact time had been reached, the residue materials were discarded. The nutrient solutions were then filtered through a 0.45 μm filter and stored in a cooler at 1°C for later analysis. Each solution was analyzed for PO_4-P (Murphy and Riley, 1962), NO_3-N, or NH_4-N (Lachat, Zellweger Analytics, Milwaukee, Wisc.). Extracts were not discolored before analysis for PO_4-P. To normalize data, results were reported as the mass of nutrient leached or sorbed per unit mass of residue material. Results were extrapolated to a unit area basis for a given surface cover using information provided by Gregory (1982).

Nutrient analysis was performed on subsamples of the crop residue materials used in the laboratory tests (table 1). Methods used to extract nutrients are described by Havis and Alberts (1993). The ground residue material was dried at 60°C for 2 h, and a 1 g sample was placed in 30 mL of deionized-distilled water in a test tube and shaken for 2 h. After the liquid extraction process, the sample was centrifuged and filtered before nutrient analysis was performed. The solutions were then analyzed for PO_4-P (Murphy and Riley, 1962), NO_3-N, and NH_4-N (Lachat, Zellweger Analytics, Milwaukee, Wisc.). Least significant difference (LSD) procedures were used to identify differences between treatment means. A probability level of 0.05 was considered significant.

RESULTS

PO_4-P LEACHING / SORPTION

Corn residue leached PO_4-P at rates ranging from 15 to 527 $\mu g\ g^{-1}$ as residue / solution contact time increased from 25 to 86400 s (table 2 and fig. 1). The initial solution concentration did not significantly affect leaching. The rate of leaching by corn residue can be estimated using the following linear equation:

$$y = 0.0059x + 26.8\ (R^2 = 0.90) \qquad (1)$$

where y is leaching amount ($\mu g\ g^{-1}$), and x is residue / solution contact time (s).

Phosphate-P was also leached from soybean residue with residue / solution contact time significantly affecting leaching rate. As contact time increased from 25 to 86400 s, soybean residue leached PO_4-P at rates ranging from 23 to 256 $\mu g\ g^{-1}$ (table 2 and fig. 1). In general, leaching of PO_4-P

Table 1. Extractable nutrient content of the crop residue (μg of nutrient g^{-1} residue).

Crop Residue	PO_4-P	NO_3-N	NH_4-N
Corn	512	163	144
Soybean	209	9	29
Wheat	112	15	61

Table 2. Change in nutrient content (μg nutrient in solution g^{-1} residue) of solution as affected by solution concentration and contact time with crop residue.[a]

Variable	Corn Residue			Soybean Residue			Wheat Residue		
	PO_4-P	NO_3-N	NH_4-N	PO_4-P	NO_3-N	NH_4-N	PO_4-P	NO_3-N	NH_4-N
Solution concentration (μg/mL)[b]									
1	157	43	84	117	2	19	0	3	35
2	155	16	70	116	0	13	-31	8	1
3	175	32	58	109	3	1	-16	16	-16
4	154	63	1	113	3	-24	-128	-15	-66
$LSD_{0.05}$	32	19	11	8	4	6	7	6	9
Contact time (sec)									
25	15	7	-7	23	2	1	19	-2	-23
250	18	7	-17	31	9	-6	-35	12	-30
2500	50	56	-22	85	7	-16	-39	7	-51
25000	194	67	105	174	13	-2	-72	10	0
86400	527	55	206	256	-21	34	-92	-11	47
$LSD_{0.05}$	35	22	12	9	5	7	8	6	10

[a] The change in nutrient content was obtained by subtracting the initial solution concentration from the final concentration, multiplying the difference by the volume of solution, and dividing the result by the residue mass. Therefore, positive changes in nutrient content indicate leaching from the crop residue, while negative values represent sorption.

[b] Solution concentrations 1, 2, 3, and 4 are 0, 4, 8, and 16 μg/mL PO_4-P and 0, 6, 12, and 24 μg/mL NO_3-N and NH_4-N.

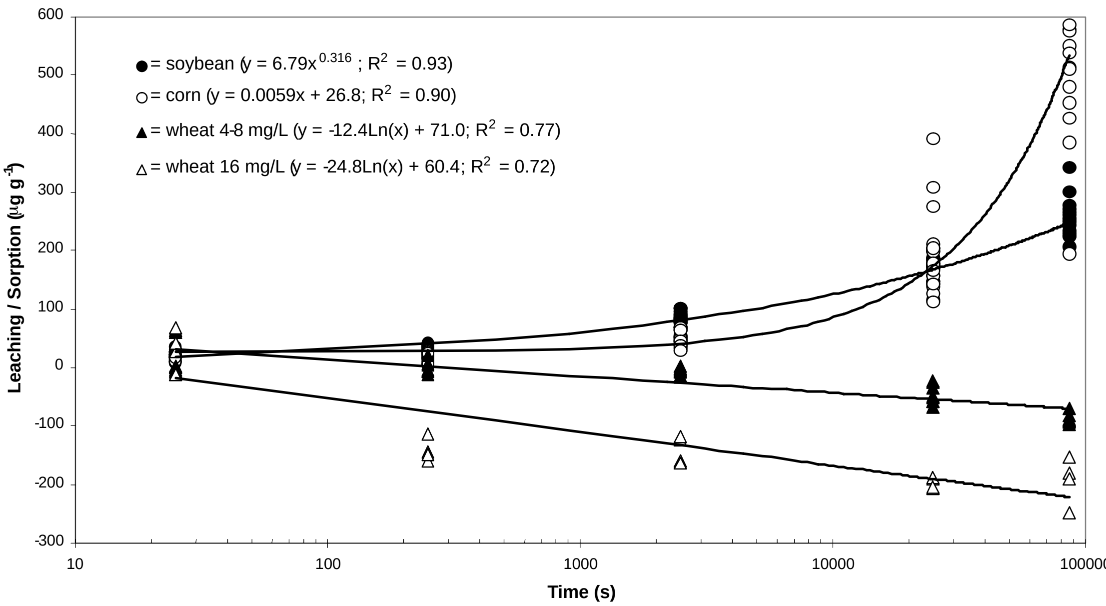

Figure 1. Leaching / sorption of PO_4-P by corn, soybean, and wheat residue.

by soybean residue increased substantially with longer contact time. Leaching rate was not significantly affected by initial solution concentration. The following equation can be used to estimate leaching of PO_4-P by soybean residue:

$$y = 6.79x^{0.316} \ (R^2 = 0.93) \qquad (2)$$

where y is leaching amount (μg g^{-1}), and x is residue / solution contact time (s).

Measured PO_4-P contents for corn and soybean residue, determined during a standardized 2 h extraction process, were approximately 512 and 209 μg g^{-1}, respectively (table 1). These values were not substantially different from the 527 and 256 μg g^{-1} of PO_4-P leached from the corn and soybean residue materials, respectively, during the 86400 s (24 h) residue / solution contact period. Thus, it appears that the P contained in the corn and soybean residues was leached in 1 d. Because corn residue contained a greater quantity of PO_4-P than soybean residue, more PO_4-P was leached from corn residue for a given residue / solution contact time.

Nutrient contents of the residue materials were obtained from replicated measurements using 1 g subsamples. In contrast, 12,000 g of corn and 8,400 g of soybean residue were used in the leaching / sorption tests. Thus, the reported residue nutrient content measurements should be considered approximate values.

Greater amounts of PO_4-P were sorbed by wheat residue as residue / solution contact time increased. As contact time varied from 250 to 86400 s, wheat residue sorbed PO_4-P at rates ranging from 35 to 92 μg g^{-1} (table 2 and fig. 1). The rate of PO_4-P leaching / sorption by wheat residue from solution concentrations of 4 or 8 mg L^{-1} can be estimated using the following equation:

$$y = -12.4 \ Ln(x) + 71.0 \ (R^2 = 0.77) \qquad (3)$$

where y is leaching / sorption (μg g^{-1}), and x is residue / solution contact time (s). For an initial PO_4-P concentration of 16 mg L^{-1}, the following equation can be used to estimate PO_4-P sorption as a function of residue / solution contact time:

$$y = -24.8 \, Ln(x) + 60.4 \; (R^2 = 0.72) \qquad (4)$$

where y is sorption (μg g^{-1}), and x is residue / solution contact time (s).

NO_3-N Leaching / Sorption

During the 25 and 250 s contact times, corn leached 7 μg g^{-1} of NO_3-N, which was significantly less than the average value of 59 μg g^{-1} leached at the other contact periods (table 2). The NO_3-N content of corn residue was approximately 163 μg g^{-1} (table 1). Thus, a substantial amount of NO_3-N remained in the corn residue after 24 h of submersion. In comparison, the NO_3-N content of the soybean and wheat residues was 9 and 15 μg g^{-1}, respectively, and therefore these residue materials had minimal impact on the NO_3-N content of the solutions. Predictive equations could not be derived to accurately describe NO_3-N leaching by the residue materials.

NH_4-N Leaching / Sorption

As solution concentration increased from 0 to 24 mg L^{-1}, the amount of NH_4-N leached by corn residue consistently decreased from 84 to 1 μg g^{-1} (table 2 and fig. 2). Corn residue sorbed NH_4-N at rates varying from 7 to 22 μg g^{-1} as residue / solution contact time ranged from 25 to 2500 s. However, an average of 156 μg g^{-1} of NH_4-N was leached during the 25000 and 86400 s contact periods. For residue / solution contact times ranging from 2500 to 86400 s, the following logarithmic equation can be used to estimate leaching / sorption of NH_4-N for initial solution concentrations of 0, 6, and 12 μg mL^{-1}:

$$y = 68.9 \, Ln(x) - 558 \; (R^2 = 0.93) \qquad (5)$$

where y is leaching / sorption (μg g^{-1}), and x is contact time (s). For an NH_4-N concentration of 24 μg mL^{-1}, leaching / sorption can be estimated from the following equation:

$$y = 47.1 \, Ln(x) - 420 \; (R^2 = 0.86) \qquad (6)$$

where y is leaching / sorption (μg g^{-1}), and x is residue / solution contact time (s).

The amount of NH_4-N leached from soybean residue decreased from 19 to 1 μg g^{-1} as solution concentration increased from 0 to 12 μg mL^{-1} (table 2 and fig. 3). In contrast, 24 μg g^{-1} of NH_4-N were sorbed as solution concentration increased to 24 μg mL^{-1}. The following equations can be used to estimate leaching / sorption of NH_4-N for initial solution concentrations of 0 and 6 μg mL^{-1}, and 12 μg mL^{-1}, respectively:

$$y = -6E{-}10x^2 + 0.0006x + 2.04 \; (R^2 = 0.77) \qquad (7)$$

$$y = 9E{-}09x^2 - 0.0002x - 9.20 \; (R^2 = 0.73) \qquad (8)$$

where y is leaching / sorption (μg g^{-1}), and x is residue / solution contact time (s).

Wheat residue either leached or sorbed NH_4-N depending on the initial solution concentration. Leaching of NH_4-N occurred for solution concentrations of 0 and 6 μg mL^{-1}, while sorption was found at concentrations of 12 and 24 μg mL^{-1} (table 2 and fig. 4). For residue / solution contact times ranging from 25 to 2500 s, wheat residue sorbed an average of 35 μg g^{-1} of NH_4-N. The following equations can be used to estimate leaching / sorption of NH_4-N for solution concentrations of 0, 6, 12, and 24 μg mL^{-1}, respectively:

$$y = 15.4 \, Ln(x) - 90.7 \; (R^2 = 0.85) \qquad (9)$$

$$y = -1E{-}08x^2 + 0.002x - 25.3 \; (R^2 = 0.90) \qquad (10)$$

$$y = 2E{-}09x^2 + 0.0012x - 52.4 \; (R^2 = 0.97) \qquad (11)$$

$$y = 1E{-}08x^2 - 0.0005x - 75.3 \; (R^2 = 0.77) \qquad (12)$$

where y is leaching / sorption (μg g^{-1}), and x is residue / solution contact time (s).

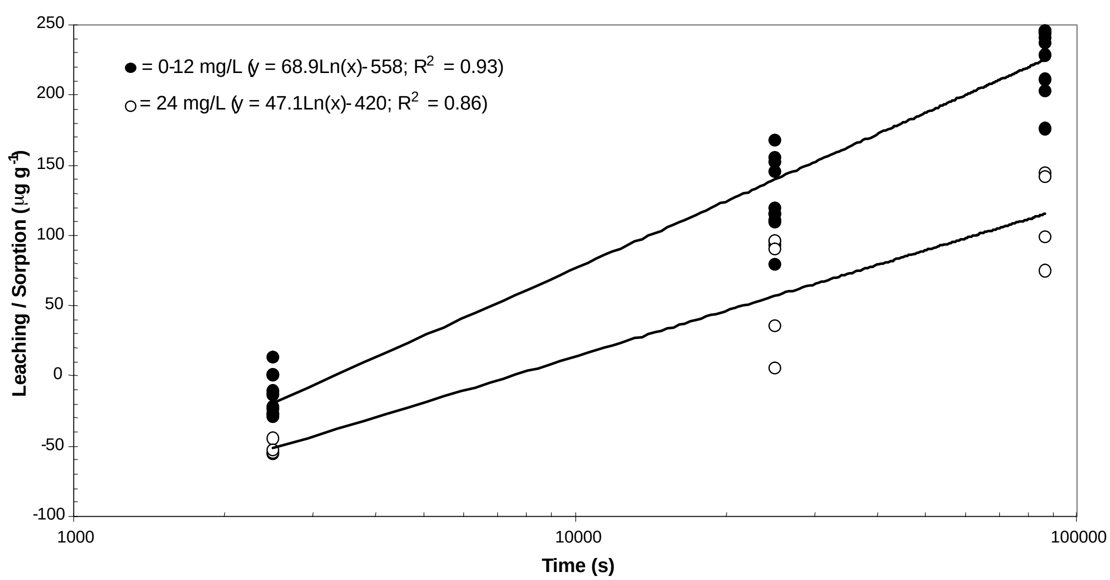

Figure 2. Leaching / sorption of NH_4-N by corn residue.

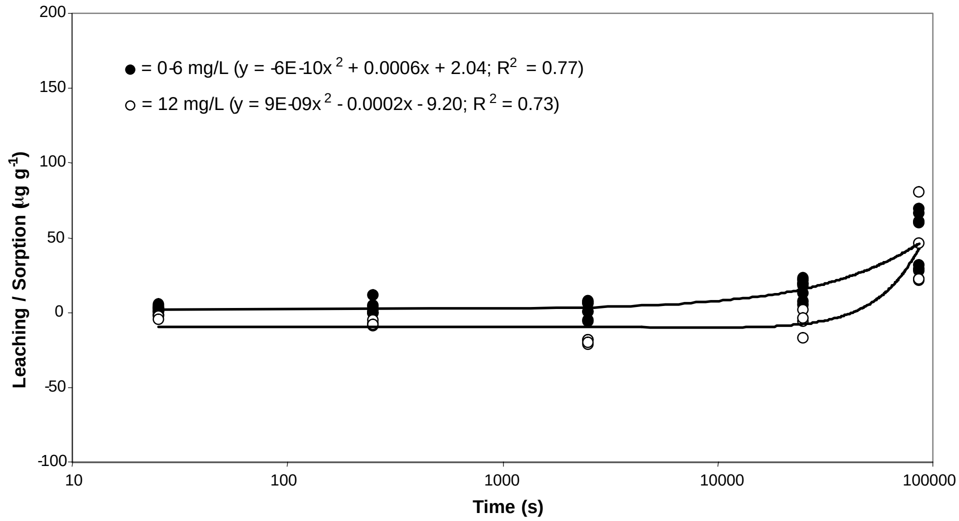

Figure 3. Leaching / sorption of NH_4-N by soybean residue.

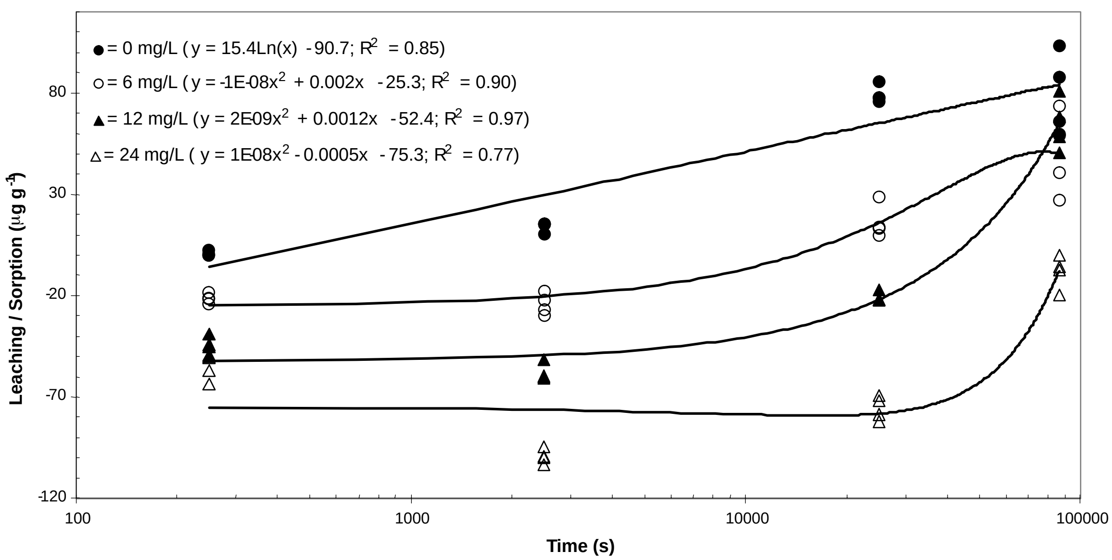

Figure 4. Leaching / sorption of NH_4-N by wheat residue.

DISCUSSION

Leaching of PO_4-P, NO_3-N, and NH_4-N usually occurred for each of the residue materials when nutrients were not found in the initial solution (table 2). If a relatively large amount of nutrient was present in the residue material, then a greater quantity of nutrient was leached into solution. Since corn residue had the largest concentration of nutrients per gram of material, nutrient concentrations were greater in the solutions containing corn residue. A substantial percentage of the nutrients within the residue materials were leached, with the exception of the 112 $\mu g\ g^{-1}$ of PO_4-P contained in wheat residue (table 1). Less than 1 $\mu g\ g^{-1}$ of PO_4-P was leached when wheat residue was placed into a solution without nutrients (table 2). Schreiber and McDowell (1985) reported that 25 mm of simulated rainfall caused 8% to 14% of the total P in wheat residue collected immediately after harvest to be leached. Before it was collected, the wheat residue used in this study had been in the field for 119 days after harvest, and thus substantial leaching of nutrients may have already taken place.

Nutrient leaching dynamics from partially decomposed corn and soybean residue were examined in a laboratory rainfall simulation experiment conducted by Havis and Alberts (1993). They found that soybean released more NO_3-N and NH_4-N per gram of residue than corn, but that corn leached more PO_4-P. In this study, substantially more PO_4-P was also released from corn than from soybean residue (table 2). However, corn was also found to leach substantially more NO_3-N and NH_4-N than soybean residue. Concentrations of PO_4-P, NO_3-N, and NH_4-N were much greater in corn than soybean residue (table 1). The proportion of nutrients in the corn and soybean materials examined by Havis and Alberts (1993) may have been different than those used in this investigation.

The application of simulated rainfall to wheat straw residue has been shown to leach PO_4-P. Schreiber (1985) and Schreiber and McDowell (1985) reported runoff-weighted PO_4-P concentrations as large as 1 to 4 mg L^{-1}. In this study, leaching of PO_4-P was found at a wheat residue / solution contact time of 25 s, while substantial sorption occurred for the other contact times. During a precipitation event, leach-

ing of PO_4-P from wheat residue may occur. However, with sufficient contact time, wheat residue may also sorb PO_4-P being transported by overland flow. With increased contact time between overland flow and wheat residue, the opportunity for sorption of PO_4-P increases. Conservation practices such as contouring, strip cropping, conservation tillage, terraces, and buffer strips can all be used to reduce runoff velocity and increase residue / runoff contact time.

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 leached 50 μg of PO_4-P per gram of residue over a 40 min period. For a corn residue cover of 79%, approximately 0.20 kg ha^{-1} of PO_4-P could be leached over 40 min. During the wet (second) rainfall simulation run, Eghball et al. (2000) measured a total PO_4-P load of 0.31 kg ha^{-1} over a 1 h period on plots without a grass hedge on which beef cattle manure was applied at a rate required to meet corn N requirements. Thus, the potential quantity of PO_4-P leached from corn residue appears to be almost as large as the amount transported in runoff from a site on which beef cattle manure was recently applied.

As another example, 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%. Using equations developed by Gregory (1982), a wheat residue mass of approximately 2.1×10^3 kg ha^{-1} was estimated for the study site. In the present study, wheat residue sorbed 39 μg of PO_4-P per gram of residue over a 40 min period. Therefore, approximately 0.082 kg ha^{-1} of PO_4-P could be sorbed during 40 min on this site with a wheat residue cover of 65%. For wheat plots on which beef cattle manure was recently added, Eghball and Gilley (1999) measured a total PO_4-P load of 0.29 kg ha^{-1} during the wet (second) rainfall simulation run. Thus, wheat residue appears to have the potential to sorb a significant percentage of PO_4-P transported by runoff from a site on which beef cattle manure was recently applied.

To use the regression equations derived in this study to estimate leaching / sorption as a function of time, the nutrient constituent of interest (PO_4-P, or NH_4-N) should first be identified. The results obtained in this investigation using NO_3-N did not provide well-established trends that allowed derivation of accurate predictive equations. Once the nutrient constituent has been selected, the residue material of interest (corn, soybean, or wheat) should be considered. For corn and soybean residue, leaching of PO_4-P was found to be independent of solution concentration, so the predictive equations (eqs. 1 and 2) can be used directly without considering solution concentration. However, to estimate sorption of PO_4-P by wheat residue (eqs. 3 and 4) or leaching / sorption of NH_4-N by corn, soybean, or wheat residue (eqs. 5 to 12), solution concentration must also be estimated. If the solution concentration of interest is not included explicitly in the predictive equations, then estimates could be made using equations that are available and the results extrapolated.

CONCLUSIONS

The following conclusions can be drawn from this study:

- Leaching and sorption of N and P by crop residue may be influenced by type of residue material, nutrient constituent, solution concentration, and residue / solution contact time.
- As residue / solution contact time increased from 25 to 86400 s, corn and soybean residue leached PO_4-P at rates ranging form 15 to 527 μg g^{-1} and 23 to 256 μg g^{-1}, respectively.
- Wheat residue sorbed PO_4-P at rates varying from 35 to 92 μg g^{-1} as residue / solution contact time increased from 250 to 86400 s.
- As residue / solution contact time increased from 25 to 86400 s, corn residue leached NO_3-N at rates ranging from 7 to 55 μg g^{-1}.
- Wheat residue sorbed an average of 35 μg g^{-1} of NH_4-N for residue / solution contact times varying from 25 to 2500 s.
- Corn and soybean residue materials could contribute to runoff nutrient load through leaching, while wheat residue appears to have the potential to sorb PO_4-P and NH_4-N transported by overland flow.

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