# Reducing Phosphorus Runoff and Inhibiting Ammonia Loss from Poultry Manure with Aluminum Sulfate[1]

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## ABSTRACT

**Applications of aluminum sulfate ($Al_2(SO_4)_3 \cdot 14H_2O$), commonly referred to as alum, to poultry litter have been shown to decrease P runoff from lands fertilized with litter and to inhibit $NH_3$ volatilization. The objectives of this study were to evaluate the effects of alum applications in commercial broiler houses on: (i) $NH_3$ volatilization (in-house), (ii) poultry production, (iii) litter chemistry, and (iv) P runoff following litter application. Two farms were used for this study: one had six poultry houses and the other had four. The litter in half of the houses at each farm was treated with alum; the other houses were controls. Alum was applied at a rate of 1816 kg/house, which corresponded to 0.091 kg/bird. Each year the houses were cleaned in the spring and the litter was broadcast onto paired watersheds in tall fescue at each farm. Results from this study showed that alum applications lowered the litter pH, particularly during the first 3 to 4 wk of each growout. Reductions in litter pH resulted in less $NH_3$ volatilization, which led to reductions in atmospheric $NH_3$ in the alum-treated houses. Broilers grown on alum-treated litter were significantly heavier than controls (1.73 kg vs. 1.66 kg). Soluble reactive phosphorus (SRP) concentrations in runoff from pastures fertilized with alum-treated litter averaged 73% lower than that from normal litter throughout a 3-yr period. These results indicate that alum-treatment of poultry litter is a very effective best management practice that reduces nonpoint source pollution while it increases agricultural productivity.**

POULTRY LITTER APPLICATIONS to pastures have been shown to result in relatively high P runoff, even when litter is applied at recommended rates (Edwards and Daniel, 1993). Most of the P in the runoff is in the soluble form (Edwards and Daniel, 1993), which is the form most available for algal uptake (Sonzogni et al., 1982). Concerns have arisen over this, since P is normally the limiting nutrient for eutrophication (Schindler, 1977).

Recent research has shown that alum additions to poultry litter can decrease P solubility in the litter by orders of magnitude (Moore and Miller, 1994). Shreve et al. (1995) found that P runoff from tall fescue (*Festuca arundinacea* Schreb.) plots fertilized with alum-treated litter was 87% lower than plots fertilized with normal litter. The fescue plots receiving alum-treated litter had significantly higher yields and higher N contents than normal litter, indicating that alum had increased N availability in the litter. We hypothesized that the increase in N availability was due to a decrease in $NH_3$ volatilization. This was confirmed in laboratory studies conducted by Moore et al. (1995, 1996), which showed alum amendments to poultry litter could reduce $NH_3$ volatilization losses by as much as 99%, compared with normal litter.

Ammonia volatilization from poultry litter results in high levels of $NH_3$ gas in the atmosphere of poultry-rearing facilities, which is very detrimental to the health of the birds and farm workers. Carlile (1984) indicated that the critical level of $NH_3$ for poultry is 25 $\mu$L/L. Above this concentration, $NH_3$ can decrease growth rates and egg production, reduce feed efficiency, damage the respiratory tract and retinas, and cause immunosuppression problems (Carlile, 1984). Reece et al. (1981) and Anderson et al. (1964) indicated that high $NH_3$ concentrations in poultry houses are more common in the winter, since high heating costs force growers to decrease ventilation. Although many different litter amendments have been tested to reduce $NH_3$ volatilization from poultry litter, the most effective are alum, ferrous sulfate, and phosphoric acid (Moore et al., 1995, 1996). Although phosphoric acid was found to be more cost-effective, it resulted in much higher concentrations of P, particularly soluble P, in the litter. Therefore, phosphoric acid is unsatisfactory in areas of the country where P runoff is accelerating eutrophication. It is interesting to note that the only area of the country where phosphoric acid has been widely used is the Delmarva Peninsula (Delaware, Maryland, and Virginia). Unfortunately, this area represents a large portion of the Chesapeake Bay Watershed, where P has been shown to negatively impact water quality.

In contrast to phosphoric acid, which can greatly increase P runoff and thus accelerate the eutrophication process, applying alum to poultry litter has been shown to significantly reduce P runoff (Shreve et al., 1995). Recent research has shown that treating poultry litter with alum will also reduce heavy metal runoff (Moore et al., 1998b) and estrogen runoff (Nichols et al., 1997).

The objectives of this study were to evaluate the effects of alum applications in commercial broiler houses on: (i) $NH_3$ volatilization (in-house), (ii) poultry production, (iii) litter chemistry, and (iv) P runoff.

## MATERIALS AND METHODS

### Broiler Production Study

Two poultry (broiler) farms were chosen for this study: one had six poultry houses and the other had four poultry houses. The litter in all of the houses was removed at the beginning of the study (spring, 1994) and fresh bedding (wood shavings) was placed in each house. After each growout, the litter was

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**Abbreviations:** SRP, soluble reactive P; TKN, total Kjeldahl N; TP, total P; EC, electrical conductivity; ICP, inductively coupled argon plasma emission spectrometer.

**Table 1. Description of soil at watersheds of Farm A.**

| | |
|---|---|
| | **Soil: Captina**<br>**County: Madison**<br>**Location: Farm A**<br>**Described and sampled by: Brian Shreve and Phillip Owens**<br>**Classification: fine-silty, siliceous, mesic Typic Fragiudult** |
| **A** | **0–17 cm Brown (10YR 4/3) silt loam; weak very find subangular blocky structure; friable; common very fine and common fine roots; common fine continuous pores; clear boundary.** |
| **Bt1** | **17–43 cm Strong brown (7.5YR 5/6) silty clay loam; moderate fine blocky structure; firm; common faint clay on faces of peds; few fine and common very fine roots; common fine and common very fine continuous pores; abrupt boundary.** |
| **Bt2** | **43–66 cm Strong brown (7.5YR 5/6) silty clay loam; moderate medium subangular blocky structure; firm; common distinct clay films on faces of peds; few fine roots; common very fine continuous pores; few medium distinct light gray (10YR 7/1) and common medium distinct pale brown (10YR 6/3) Fe depletions; few fine distinct dark red (2.5YR 4/6) Fe concentrations; gradual boundary.** |
| **Bt3** | **66–89 cm Strong brown (7.5YR 5/6) silty clay loam; moderate medium subangular blocky structure; firm; common distinct clay films on faces of peds; common fine continuous pores; common medium distinct light gray (10YR 7/1) and few medium distinct pale brown (10YR 6/3) Fe depletions; common coarse distinct dark red (2.5YR 4/6) and few fine distinct brownish yellow (10YR 6/8) Fe accumulations; clear boundary.** |
| **Btx** | **89–152+ cm Dark red (10R 3/6) silty clay; moderate medium angular blocky structure; very firm and brittle in 60% of matrix; common distinct clay films on faces of peds; common very fine continuous pores; many medium prominent and many coarse prominent light gray (10YR 7/1) and common fine distinct yellowish brown (10YR 5/8) Fe depletions; boundary not observed.** |

de-caked (a process in which the uppermost layer of manure, which is usually very moist and caked together, is removed), using a commercial de-caking machine. Then alum was applied to the litter in half the houses on each farm; the remaining houses were controls. The rate the alum was applied was 1362 kg/house after the first growout (first year only) and 1816 kg/house after subsequent growouts. Alum was not applied after the last growout before cleanout. Ammonia measurements, energy use, litter chemistry, and broiler production parameters were evaluated. Ammonia levels were measured weekly using dragger tubes. Each house was equipped with its own electric meter and electricity use was evaluated weekly. Each house also had its own propane tank. Propane receipts were obtained from the growers. Broiler weights were determined by the integrator (poultry company) for four growouts on Farm A and three growouts on Farm B. Feed conversion was determined three times at Farm B and was not determined at Farm A. Litter pH and atmospheric $NH_3$ concentrations were determined weekly. Three litter samples were taken from each house. To sample the litter in each house, they were divided longitudinally into thirds. A soil corer (2.54-cm i.d.) was used to collect 15 to 20 samples from each third of the house. Samples were taken from the surface to just above the soil/litter interface (resistance to the corer becomes strong at this interface, allowing the sampler to determine how deep to sample). In the lab, a 20-g subsample of the litter was weighed out into 250-ml polycarbonate centrifuge tubes and shaken with 200 mL of deionized water (at a 1:10 litter/water ratio) for 2 h. The samples were centrifuged for 20 min at $4066 \times g$ and unfiltered aliquots were used for pH measurements.

At the end of the first annual cycle, litter samples were taken for chemical characterization (Moore et al., 1998). Total N was determined by Kjeldahl distillation after using the salicylic acid modification of the Kjeldahl digestion to include $NO_3$ (Bremner and Mulvaney, 1982) using moist samples (values were corrected for water content). Moist samples were used because oven drying resulted in N losses. Total metals and total P were determined by digesting oven-dried (60°C) litter with $HNO_3$ and analyzing the digested sample using ICP (inductively coupled argon plasma emission spectrometer) (Zarcinas et al., 1987).

To measure $NH_3$ fluxes, 18 simple $NH_3$ flux chambers were constructed from plastic buckets (Moore et al., 1997c). Three of these chambers were randomly placed in each of six poultry houses at Farm A during the fifth growout and the concentration inside the chambers was measured immediately after placement and 1 h later using dragger tubes (Sensidyne ammonia-detection tubes). Dragger tubes contain a resin that reacts quantitatively with $NH_3$, changing color in the process. Three litter samples were also taken from each house at this time and used for pH determination, as previously described. For more details on this simple method for measuring relative $NH_3$ fluxes from animal manure, see Moore et al. (1997c).

## Runoff Study

The soil at Farm A was a Captina silt loam (fine-silty, siliceous, mesic, Typic Fragiudult). The soil at Farm B was a Pickwick silt loam (fine-silty, mixed, mesic, Typic Hapludult). The soils were classified by Brian Shreve and Phillip Owens

**Table 2. Description of soil at watersheds of Farm B.**

| | |
|---|---|
| | **Soil: Pickwick**<br>**County: Washington**<br>**Location: Farm B**<br>**Described and sampled by: Brian Shreve and Phillip Owens**<br>**Classification: fine-silty, mixed, mesic Typic Hapludult** |
| **Ap** | **0–24 cm Dark brown (7.5YR 3/3) silt loam; moderate fine subangular blocky structure; friable; many very fine roots; common fine continuous pores; clear boundary.** |
| **BA** | **24–42 cm Brown (7.5YR 4/3) silt loam; moderate medium subangular blocky structure; friable; common very fine roots; many very fine continuous pores; abrupt boundary.** |
| **Bt1** | **42–63 cm Reddish brown (5YR 4/4) silt loam; moderate medium subangular blocky structure; friable; few distinct clay films on faces of peds; common very fine roots; common very fine continuous pores; few fine distinct black (7.5YR 2.5/1) Mn stains on faces of peds; gradual boundary.** |
| **Bt2** | **63–94 cm Yellowish red (5YR 4/6) silty clay loam; moderate coarse subangular blocky structure; firm; common prominent 2.5YR 3/6 clay films on faces of peds; few very fine roots; common fine and common very fine continuous pores; few fine distinct pinkish gray (7.5YR 7/2) Fe depletions; abrupt boundary.** |
| **Bt3** | **94–114+ cm Reddish brown (5YR 4/4) silty clay loam; moderate fine subangular blocky structure; firm; common distinct clay films on faces of peds; few very fine continuous pores; common fine distinct pinkish gray (7.5YR 7/2) and common fine distinct strong brown (7.5YR 5/6) Fe depletions; common fine black (N 2.5/) Mn stains; rounded 5-mm to 10-mm chert fragments 55% by volume; boundary not observed.** |

(Tables 1 and 2). Two watersheds (0.405 ha) were constructed side-by-side at both farms (described previously). The watersheds were formed by building earthen berms using topsoil brought in from offsite. After the berms were constructed, the watersheds were equipped with approaches and flumes. Small sheds were built adjacent to each flume to house automatic water samplers (American Sigma Corp., Medina, NY). Barbed-wire fences were built around the watersheds to keep cattle out.

The dirt work for the berms was completed in August 1994. After construction, the berms were sprayed with hydromulch containing tall fescue (*Festuca arundinacea* Schreb) seed. The water samplers were installed and operational by January 1995. Each sampler was programmed to sample at 1, 3, and 7 min after runoff; afterward the sampler switched to a volume mode and sampled every 379 L (100 gallons). A record of the amount of runoff from each event was made using a pressure transducer, although on one occasion the transducer was not properly calibrated or it malfunctioned altogether. Hence, runoff volume data from this study was incomplete (and somewhat suspect).

Poultry-litter applications were made using a commercial litter-spreading truck. Application rates (on an as-is basis) were 4460 kg/ha (2.5 tons/acre) in 1995; in 1996 and 1997 the application rate was 7136 kg/ha (4 tons/acre). The litter was spread in April or May of each year, as is the normal practice in northwest Arkansas. The forage (tall fescue) produced on the watersheds was either hayed or mowed, depending on the season and amount of forage present. Mowing produced a thick thatch layer, which is somewhat atypical of pastures or hay meadows in northwest Arkansas.

The water samplers were checked after every rainfall to determine if runoff had occurred. When runoff occurred, the information from the runoff was downloaded from the water samplers to a portable computer. Then the sample bottles were changed out for new bottles and the samples were returned to the lab.

During the first year of the runoff study, the water samples were analyzed for pH, electrical conductivity (EC), soluble reactive P (SRP), soluble metals, $NO_3$-N, $NH_4$-N, soluble organic C, total P (TP), total metals, total N, and total C. During the second and third years of the study, the water was

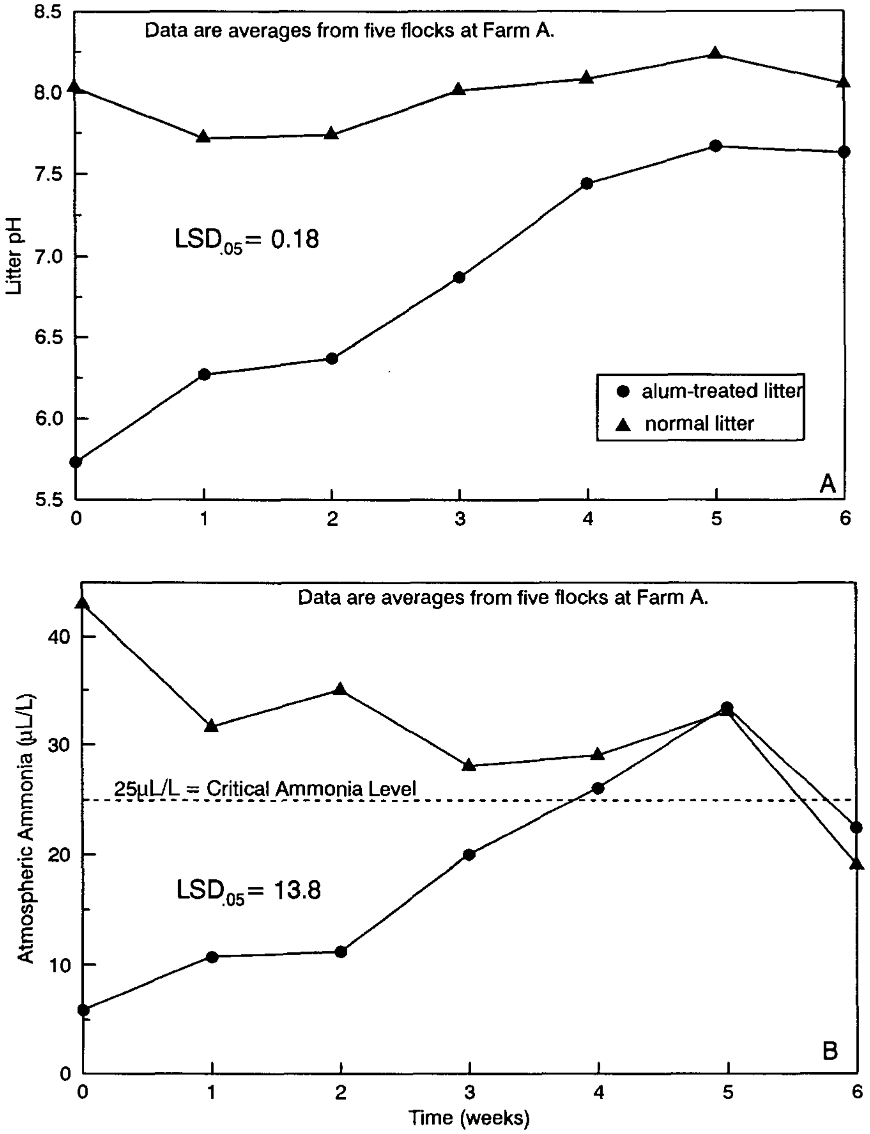

**Fig. 1. (*A*) Litter pH with and without alum as a function of time. (*B*) Atmospheric $NH_3$ data in poultry houses with and without alum as a function of time.**

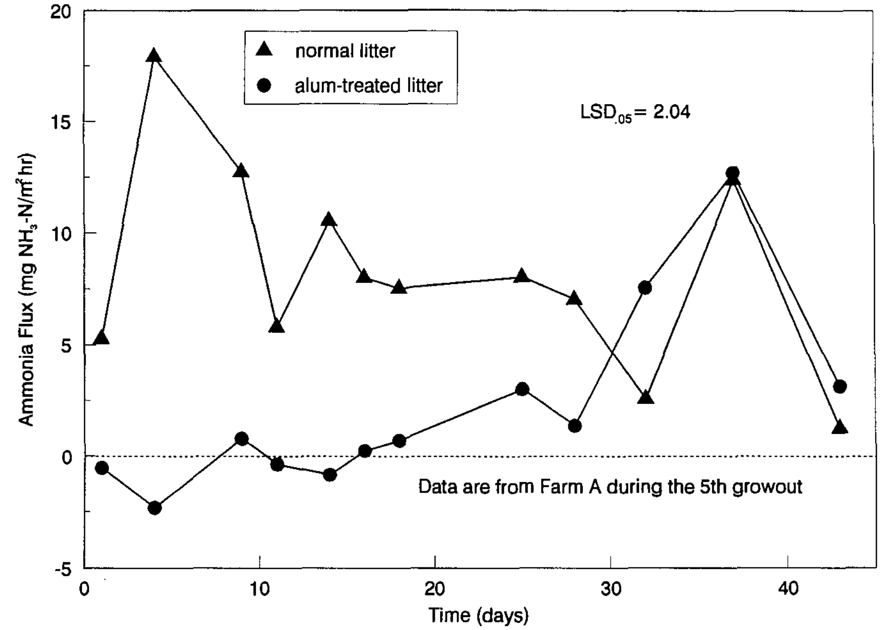

Fig. 2. **Ammonia fluxes from alum-treated and normal poultry litter as a function of time.**

analyzed for SRP and TP. The pH and EC were measured on unfiltered samples. Samples were filtered through 0.45-m filter papers for $NH_4$–N, $NO_3$–N, SRP, and soluble metals. Samples for P and soluble metals were acidified to pH 2 with HCl before being frozen, whereas $NH_4$–N and $NO_3$–N samples were not. Unfiltered (acidified) samples were used for TP, TKN (total Kjeldahl N), and total metal analysis. Samples for TKN were digested using sulfuric acid with $K_2SO_4$ and $HgSO_4$ as catalysts (USEPA, 1979). Ammonium was determined with the salicylate–nitroprusside technique, according to EPA method 351.2 (USEPA, 1979). Nitrate (+nitrite) was determined using the Cd-reduction method, according to Method APHA 418-F (APHA, 1992). Nitrate concentrations in runoff water were very low (<1% of inorganic N) and are not reported. Soluble reactive P was determined using the ascorbic-acid technique with an auto-analyzer according to APHA method 424-G (APHA, 1992). Total metals and TP were determined by ICP following a nitric-acid digestion (EPA method 3030E). Soluble organic C was determined as the difference between total organic C and inorganic C, as measured on a Rosemont DC-190 organic C analyzer (Rosemount Analytical, Santa Clara, CA).

Four stainless-steel lysimeters (0.45-m pores) were also placed in each watershed to evaluate $NO_3$–N leaching. These were normally placed about 50 cm below the soil surface. Every week a suction was pulled on the lysimeters and soil solutions were sampled when possible. Nitrate analyses were conducted, as described earlier. Soil samples were also taken for $NO_3$–N analysis before litter application and at 2 wk, 3 mo, 9 mo, and 1 yr after the initial fertilization. Cores were taken to a depth of 1 m (when possible) and segmented into five depths for analyses (0–20, 20–40, 40–60, 60–80, and 80–100

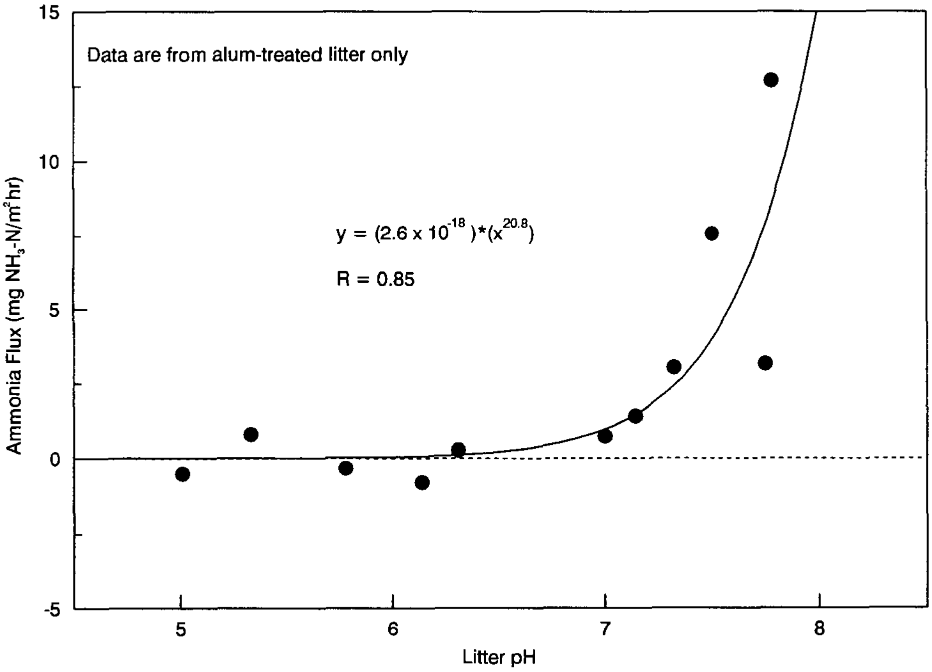

Fig. 3. **Ammonia fluxes from alum-treated litter as a function of pH.**

cm). Four cores were taken from each watershed each time for these analyses. After oven drying at 70°C, the samples were ground to pass a 20-mesh sieve and extracted with deionized water (at a 10:1, water/soil ratio) for 1 h on a shaker. After centrifuging for 20 min at 4066 × *g* (6000 rpm), the samples were filtered and analyzed for $NO_3$–N, as previously described.

All statistical analysis of these data were performed using PROC GLM of SAS (1985). The probability value used to determine significance was 0.05. Differences between means were evaluated using Fisher's Protected LSD. For the runoff data, the effect of treatment was tested using runoff event for replication.

## RESULTS AND DISCUSSION

### Litter pH

Aluminum sulfate (alum) applications lowered the litter pH significantly, particularly during the first 3 to 4 wk after the beginning of each growout (Fig. 1A). As the amount of manure produced by the birds increased, the pH of the litter increased, until the birds were about 4 or 5 wk old, when the litter pH leveled off at 7.5. The litter pH for the control birds remained relatively constant (8) throughout the study. This reduction in pH due to alum is expected to occur, since alum is a dry acid with 6 moles of protons formed for each mole of alum dissociated, as shown in Eq. [1]:

$$Al_2(SO_4)_3 \cdot 14H_2O + 6H_2O \rightarrow 2Al(OH)_3 + 3SO_4^{2-} + 6H^+ + 14H_2O \quad [1]$$

### Atmospheric Ammonia

Reductions in litter pH decreased $NH_3$ volatilization from the litter, which resulted in significant reductions in atmospheric $NH_3$ in the alum-treated houses, compared with controls (Fig. 1B). The average ammonia concentration in the control houses was above 25 μL $NH_3$–N/L for the first 5 wk of the growout. Decreases in weight gains and poor feed conversion have been demonstrated at this level (Carlisle, 1984; Reece et al., 1981). Ammonia concentrations in the alum-treated houses were very low the first 3 to 4 wk of the study, which coincides with the stage of growth when birds are the most sensitive to high $NH_3$.

Decreases in $NH_3$ volatilization from alum-treated litter have been reported by Moore et al. (1995, 1996). When alum lowers litter pH, it shifts the $NH_3/NH_4^+$ towards $NH_4^+$, which is not volatile (Eq. [2]):

$$NH_3 + H^+ \rightarrow NH_4^+ \quad [2]$$

One aspect of high $NH_3$ levels in poultry-rearing facilities that is often overlooked is the effect on the grower. Farm workers frequently spend 8 to 10 h/d in poultry houses, particularly when the birds are young. Normally, this period coincides with the highest $NH_3$ levels—at times exceeding 100 μL/L. In Europe, COSSH (Control of Substances Hazardous to Health) has set the limit of $NH_3$–N human exposure to ammonia at 25 μL/L for an 8-h d and 35 μL/L for a 10-min exposure (Williams, 1992). The effect on humans from years of chronic exposure to relatively high levels of ammonia warrants investigation.

### Ammonia Fluxes

The ventilation for the 10 poultry houses used for this study was controlled by the growers. Since $NH_3$ emissions were much higher for normal litter than alum-treated litter, the growers greatly increased the ventilation rates of the control houses. Therefore, the atmospheric $NH_3$ data does not accurately describe $NH_3$ volatilization. Hence $NH_3$ flux measurements were made to ascertain the relative differences in volatilization rates.

Ammonia fluxes were significantly reduced by the

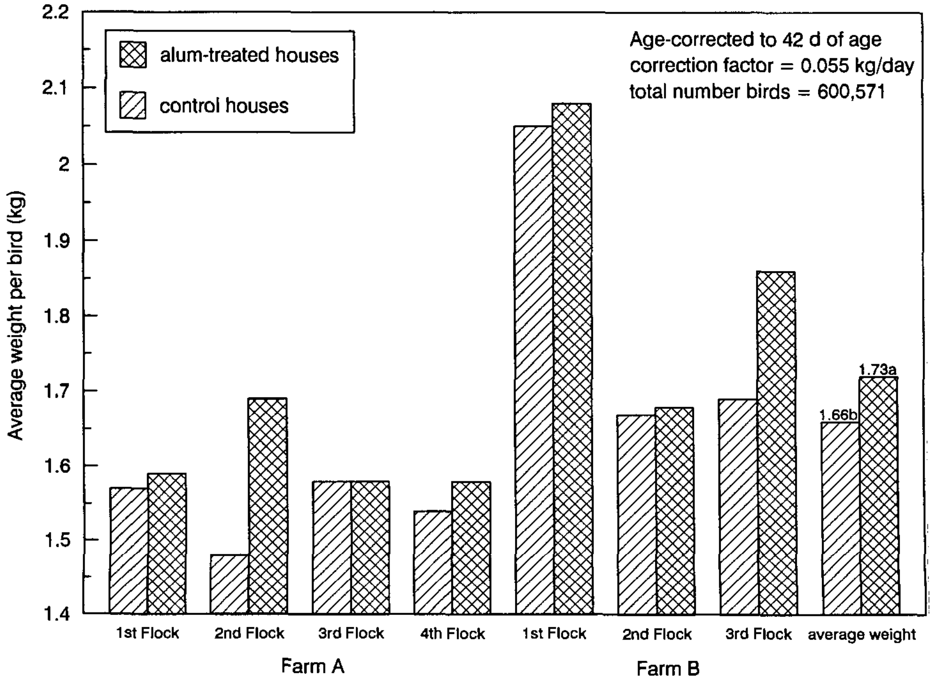

**Fig. 4. Chicken body weights at 42 d, grown in houses with and without alum.**

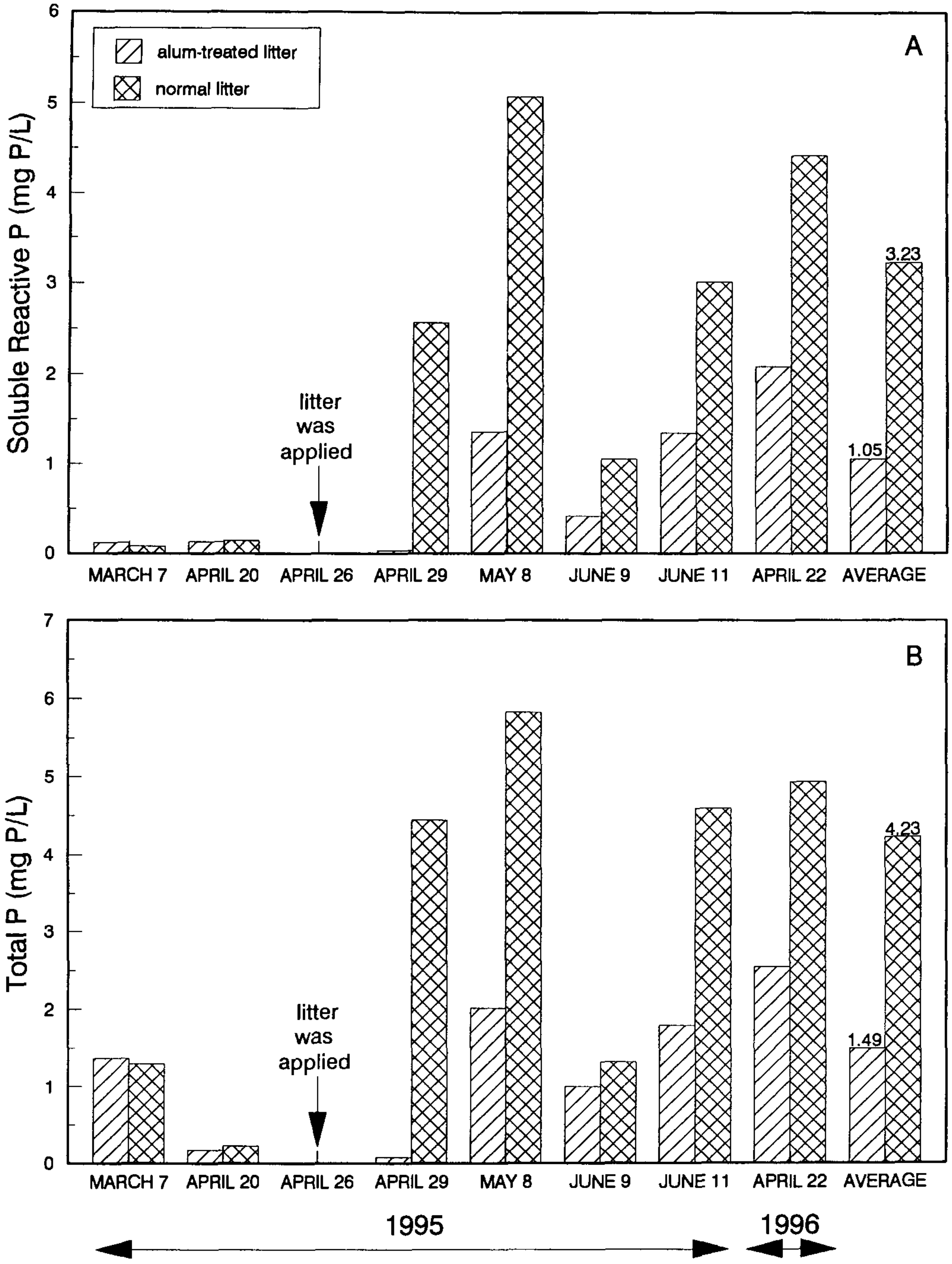

**Fig. 5. Phosphorus runoff from fields fertilized with alum-treated and normal litter for first year of the study. (*A*) Soluble Reactive P vs. date; (*B*) Total P vs. date.**

alum treatment for the first 4 wk (Fig. 2). During this period, the average $NH_3$ flux was 0.11 mg $NH_3$–N $m^{-2}$ $h^{-1}$, compared with 9.49 mg $NH_3$–N $m^{-2}$ $h^{-1}$ for the control litter. This represents a 99% reduction in $NH_3$ volatilization. After the first 4 wk, volatilization rates between the treated and untreated litter followed similar trends. The reason for this is two-fold: First, the birds begin to produce a lot of manure at this stage of growth, which buries the alum-treated litter. Secondly, the pH of the alum-treated litter increases as new manure is added to it. When the pH exceeds 7, the $NH_3$ volatilization rate increases rapidly (Fig. 3). Ammonia volatilization is a very pH-dependent process (Reddy et al., 1979).

Overall, the $NH_3$ fluxes were about 75% lower for alum-treated litter than for normal litter (2.14 vs. 8.27 mg $NH_3$ $m^{-2}$ $h^{-1}$). Note that although the method used for these measurements gives excellent relative values, the true volatilization rate will be much higher. The technique was compared with that of Brewer (1998) in another study on the effects of alum on $NH_3$ volatilization. Although the two methods were highly correlated to each other as far as relative differences, the values

Table 3. Chemical characteristics of alum-treated and normal poultry litter after five growouts (adapted from Moore et al., 1997a).

| | Alum-treated litter | | Normal litter | |
|---|---|---|---|---|
| Parameter | Avg. | SD | Avg. | SD |
| pH | 7.59 | 0.77 | 8.04 | 0.18 |
| EC | 10 833 | 471 | 6 611 | 311 |
| | g/kg | | | |
| N | 38.5 | 1.1 | 34.5 | 2.7 |
| S | 33.9 | 9.8 | 6.8 | 0.4 |
| Ca | 29.4 | 3.6 | 34.1 | 4.2 |
| K | 27.4 | 2.7 | 26.4 | 1.6 |
| P | 18.9 | 1.8 | 22.4 | 1.7 |
| Al | 18.7 | 6.0 | 1.18 | 0.2 |
| Na | 7.54 | 0.6 | 7.85 | 0.6 |
| Mg | 5.79 | 0.7 | 6.57 | 0.4 |
| | mg/kg | | | |
| Fe | 1717 | 312 | 1095 | 155 |
| Mn | 893 | 216 | 956 | 134 |
| Cu | 679 | 93 | 748 | 102 |
| Zn | 598 | 51 | 718 | 69 |
| B | 46 | 4 | 51 | 4 |
| Ti | 31 | 11 | 44 | 19 |
| As | 20 | 8 | 43 | 4 |
| Ni | 21 | 5 | 15 | 2 |
| Pb | 8 | 2 | 11 | 2 |
| Co | 6 | 2 | 6 | 1 |
| Mo | 5 | 0.5 | 6 | 0.5 |
| Cd | 3 | 0.4 | 3 | 0.2 |

Table 4. Average chemical composition of water soluble components in runoff from pastures before fertilization (average of two events).

| | West watershed† | East watershed |
|---|---|---|
| pH | 6.24a | 6.27a |
| EC (μS/cm) | 21a | 19a |
| | mg/L | |
| SRP | 0.11a* | 0.13a |
| Ammonium-N | 0.27a | 0.23a |
| Nitrate-N | 0.25a | 0.20a |
| SOC | 7.32a | 8.56a |
| Al | 0.17a | 0.27a |
| As | 0.03a | 0.02a |
| B | 0.02a | 0.03a |
| Ca | 0.95a | 1.21a |
| Cd | BDL‡ | BDL |
| Cr | BDL | BDL |
| Cu | 0.02a | 0.01b (detection limit = 0.012) |
| Fe | 0.10a | 0.18a |
| K | 1.94a | 3.38a |
| Mg | 0.24a | 0.33a |
| Mn | 0.01a | 0.02a |
| Mo | 0.01a | 0.01a |
| Na | 1.04a | 1.03a |
| Pb | 0.02a | 0.01a |
| S | 0.66a | 0.78a |
| Se | 0.02a | 0.01a |
| Ti | BDL | BDL |
| Zn | 0.95a | 1.15a |

* Different letters indicate significant differences at the 0.05 level.

† The west watershed was later fertilized with normal litter and the east watershed with alum-treated litter.

‡ BDL = below detection limits.

obtained using Brewer's improved flux chamber were about 30 times higher. This is expected, since his method measures flux for much shorter time periods (<10 min), which reduces the chances of distorting the concentration gradient of $NH_3$ over the litter (Brewer's method also uses an infrared $NH_3$ analyzer, which was more accurate than our method). We used a 1-h flux measurement period, which resulted in a buildup of $NH_3$ in the chambers that would be expected to reduce the concentration gradient of ammonia, slowing down the flux.

Brewer (1998) found that alum applications applied at the recommended rate (0.091 kg/bird) resulted in a net $NH_3$ flux of zero for the first 3 wk of a growout, whereas alum applied at the 0.05 kg/bird rate reduced $NH_3$ emissions by 52%, compared with controls during this time. During the entire 6-wk growout, Brewer (1998) estimated the total N release from a poultry house with 20 000 broilers would be 131 kg for an alum-treated house (at the recommended rate) and 296 kg for an untreated house. This is same order of magnitude of flux that would be predicted based on our data on total N after five flocks (3.45% N for control and 3.85% N for alum-treated). It should be noted that $NH_3$ emissions are also detrimental because they result in acid precipitation (Ap Simon et al., 1987; van Breemen et al., 1982) and atmospheric ammonia deposition to aquatic systems (Schroder, 1985).

## Poultry Production

Weight data were obtained for more than 600 000 birds. Broilers grown on litter treated with alum were significantly heavier ($\alpha = 0.05$) than the controls. Average bird weights were 1.66 kg for control birds and 1.73 kg for birds grown on alum-treated litter (Fig. 4). The integrators did not always harvest the birds from all of the houses at each farm on the same day. Therefore, the bird weight data were corrected to 42 d of age using a correction factor of 0.055 kg/d. This correction factor was given to us by the Complex Manager at Farm B. The Complex Manager of Farm A indicated that this was an accurate correction factor for their birds as well.

The reason for increases in body weights due to alum are not known. At present, we hypothesize that it was

Table 5. Average total elemental analysis of runoff water from pastures before fertilization (average of two events).

| Element | West watershed† | East watershed |
|---|---|---|
| | mg/L | |
| TKN | 2.42a* | 2.66a |
| TP | 0.77a | 0.77a |
| Al | 30.2a | 28.6a |
| As | 0.01a | 0.01a |
| B | 0.10a | 0.07a |
| Ca | 3.00a | 2.81a |
| Cd | 0.01a | 0.01a |
| Cr | 0.04a | 0.04a |
| Cu | 0.03a | 0.02a |
| Fe | 14.1a | 13.5a |
| K | 5.76a | 5.99a |
| Mg | 2.42a | 2.26a |
| Mn | 0.54a | 0.60a |
| Mo | BDL‡ | BDL |
| Na | 0.40a | 0.45a |
| Pb | 0.03a | 0.03a |
| S | 0.78a | 0.80a |
| Se | 0.005a | 0.004a |
| Ti | 0.45a | 0.45a |
| Zn | 0.17a | 0.14a |

* Different letters indicate a significant difference at the 0.05 level.

† The west watershed was later fertilized with normal litter and the east watershed with alum-treated litter.

‡ BDL = below detection limits.

Table 6. Average chemical composition of water soluble components in runoff water from pastures fertilized with normal or alum-treated litter (average of five events).

| | Normal litter | Alum-treated litter |
|---|---|---|
| pH | 6.40a | 6.25a |
| EC ($\mu$S/cm) | 109a | 96.7a |
| | mg/L | |
| SRP | 3.23a* | 1.05b |
| Ammonium-N | 2.14a | 2.13a |
| Nitrate-N | 1.55a | 1.80a |
| SOC | 29.6a | 26.9a |
| Al | 0.17a | 0.35a |
| As | 0.03a | 0.06a |
| B | 0.03a | 0.03a |
| Ca | 6.92a | 4.83a |
| Cd | BDL | BDL |
| Cr | 0.01a | 0.02a (detection limit = 0.014) |
| Cu | 0.06a | 0.04a |
| Fe | 0.10a | 0.19a |
| K | 17.4a | 13.1a |
| Mg | 2.55a | 1.75a |
| Mn | 0.02a | 0.02a |
| Mo | 0.01a | 0.01a |
| Na | 1.88a | 1.43a |
| Pb | 0.04a | 0.04a |
| S | 1.74a | 1.84a |
| Se | 0.04a | 0.03a |
| Ti | 0.00a | 0.01a |
| Zn | 0.24a | 0.31a |

* Different letters indicate a significant difference at the 0.05 level.

either due to the decrease in atmospheric $NH_3$ levels or due to a change in the microbiology of the litter, both of which would be related to changes in litter pH. Scantling et al. (1995) found *E. coli* and total coliform counts were significantly reduced when poultry litter was treated with alum. Line (1998) showed that alum applications to litter significantly reduced *Salmonella* and *Campylobacter* populations in litter and completely eliminated *Campylobacter* on 6-wk-old poultry carcasses. However, we believe most of the increases in body weight were probably due to reduced $NH_3$ levels. Reece et al. (1981) showed that exposing chicks to relatively low concentrations of $NH_3$ (25 $\mu$L/L) for the first 28 d reduced body weights by 4%. The difference in average weight between control and alum-treated birds observed in this study was also 4%.

Table 7. Average total elemental analysis of runoff water from pastures fertilized with alum-treated or normal poultry litter (average of five events).

| Element | Normal litter | Alum-treated litter |
|---|---|---|
| | mg/L | |
| TKN | 4.94a* | 3.89a |
| TP | 4.23a | 1.49b |
| Al | 0.82a | 1.60a |
| As | 0.04a | 0.09a |
| B | 0.08a | 0.08a |
| Ca | 7.94a | 5.33a |
| Cd | 0.01a | 0.01a |
| Cr | 0.01a | 0.03a |
| Cu | 0.05a | 0.04a |
| Fe | 0.49a | 0.77a |
| K | 17.6a | 12.8a |
| Mg | 2.83a | 2.00a |
| Mn | 0.08a | 0.06a |
| Mo | 0.01a | 0.01a |
| Na | 2.05a | 1.71a |
| Pb | 0.04a | 0.08a (detection limit = 0.08) |
| S | 2.06a | 2.13a |
| Se | 0.04a | 0.08a |
| Ti | 0.02a | 0.04a |
| Zn | 0.12a | 0.15a |

* Different letters indicate a significant difference at the 0.05 level.

Feed conversion (the amount of feed consumed [kg] to produce a given weight [kg], hence a unitless quantity) was also better for birds grown on alum-treated litter, compared with controls (1.98 vs. 2.04). Lower feed conversions dramatically reduce production costs, since feed is the major cost for poultry production. Although feed conversion data were obtained from three flocks of birds at Farm B, the data could only be used from two of those flocks, since the birds living in untreated houses were harvested much earlier than those in alum-treated houses on the third flock (for no apparent reason). Mortality tended to be lower (although not significantly) for birds grown in alum-treated houses. Other benefits of alum-treatment were noticed in this study: Electricity and propane (gas used for winter heating) use were lower for alum-treated houses than controls. Higher energy use in the control houses was a result of higher ventilation rates, particularly in the winter, needed to reduce $NH_3$ levels. Moore et al. (1997b) indicated that the cost of alum treatment for a typical poultry house was $480 and the benefits obtained from the use of alum were $940. Hence, the benefit/cost ratio of this practice is 1.96, indicating that it is a very cost-effective best management practice.

## Litter Chemical Characteristics

The chemical characteristics of the litter from the houses at Farm A are shown in Table 3. These data indicate that alum-treated litter is similar to normal litter, except for total Al and total S, which were both much higher in the alum-treated litter. Decreases in ammonia volatilization also resulted in higher total N content of the litter in the alum-treated houses, which should result in higher crop yields. The alum-treated litter had a slightly lower pH than normal litter (7.59 vs. 8.04) and a higher electrical conductivity (10 833 S/cm vs. 6611 S/cm). The salts associated with the increased conductivity would be ammonium sulfate, calcium sulfate, and potassium sulfate. Several other metals, such as Ca, were lower in alum-treated litter than normal litter (Table 3). This is probably a dilution effect from adding alum (10% by weight).

## Storm Events and Runoff

Runoff was collected from both watersheds at Farm A on seven dates throughout the first year of the study, whereas runoff was never observed from both watersheds at Farm B on the same dates during the first year. The reasons for this difference in hydrology are twofold: (i) the hydraulic conductivity of the soils at Farm B was significantly higher than that at Farm A (Tom Sauer, unpublished data, 1996), and (ii) the slopes at Farm B were not as steep as the slopes at Farm A. Hence, monitoring of the watersheds at Farm B was discontinued after the first year.

It should also be noted that the pasture management used for this study would have a large impact on runoff and infiltration. As stated earlier, the watersheds were

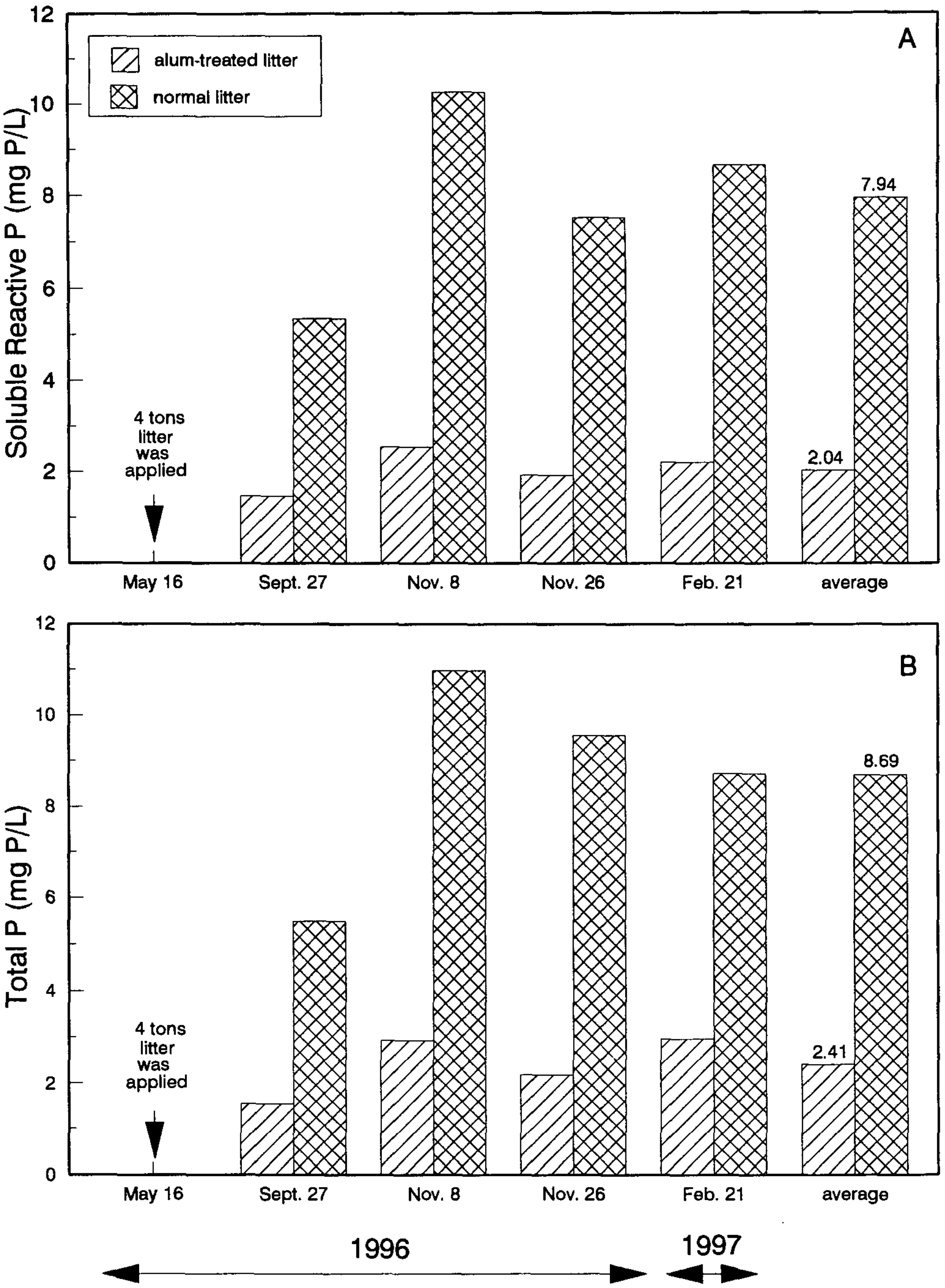

**Fig. 6.** Phosphorus runoff from fields fertilized with alum-treated and normal litter for second year of the study. (*A*) Soluble Reactive P vs. date; (*B*) Total P vs. date.

fenced to keep cattle out, so that the P from the cattle manure would not have a confounding effect on the study. However, fencing the cows out caused big differences in the canopy and soil conditions inside the fenced area vs. the rest of the pasture. On both farms, the grasses were normally kept quite short by cattle grazing, whereas in the fenced areas the grass was allowed to get tall, especially when it was being cut for hay. The fenced area also lacked cattle trails and appeared to be much less compacted than the surrounding pasture. Added to these differences was the effect of mowing (particularly in fall), which resulted in a thick layer of thatch on the surface of the soil. As a result of these differences in management between the watersheds and the pastures as a whole, we believe we had much less runoff than what would have normally occurred on these farms. On one occasion during a heavy rainfall, runoff was observed from the pasture surrounding the watersheds at Farm B, while no runoff was occurring within the watersheds. This event occurred in late spring, when the forage at Farm B within the watersheds was tall. This observation warrants further investigation into the effects of heavy grazing vs. haying pastureland on runoff and infiltration.

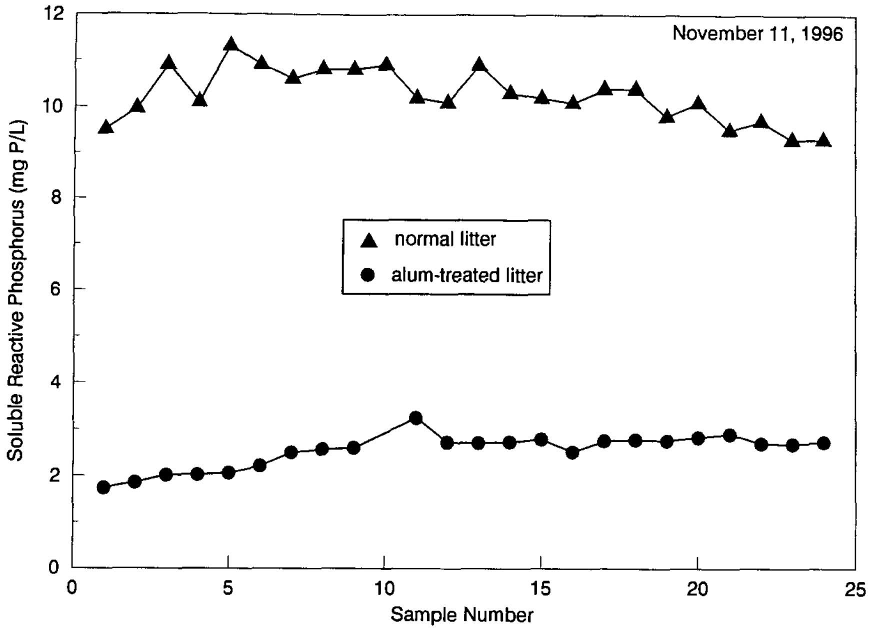

**Fig. 7. Soluble reactive P in runoff water from land fertilized with alum-treated and normal litter.**

## Phosphorus Runoff

Soluble reactive P (SRP) concentrations in runoff water from the watersheds fertilized with alum-treated and control litter were similar before litter application (0.13 and 0.11 mg P/L, respectively), as was total P concentrations (0.77 and 0.77 mg P/L) in runoff (Fig. 5A and 5B, Tables 4 and 5). However, after litter applications both the SRP and TP concentrations in runoff from normal poultry litter were significantly higher than those from alum-treated litter (Fig. 5A and 5B, Tables 6 and 7). Soluble reactive P concentrations in runoff water were 1.05 and 3.23 mg P/L for the alum-treated and normal litter, respectively, during the first yr, indicating alum reduced SRP runoff by 67%. Total P followed the same trends, with runoff water having an annual average of 1.49 and 4.23 mg P/L for runoff from alum-treated and control litter.

Total P loads for the first year were 0.75 and 3.91 kg P/ha for runoff from the watersheds fertilized with alum-treated and normal litter, respectively. Total P loads were calculated using the concentrations shown in Fig. 5B and the flow data obtained from the pressure transducers. As mentioned in the Materials and Methods section, we had some problems with flow measurements (due to the transducers), hence our main focus for this study has been on P concentrations rather than loads.

Phosphorus runoff from the watersheds during the second year are shown in Fig. 6A and 6B. Soluble reactive P concentrations were 74% lower from the field fertilized with alum-treated litter during the second year after application (2.04 and 7.94 mg P/L for the alum-treated and normal litter, respectively). Total P concentrations in runoff were 2.41 and 8.69 mg P/L, respectively, for the alum-treated and control litter. Phosphorus runoff during the third year followed the same trends (data not shown), with the annual average SRP concentrations of 1.70 and 7.69 mg P/L for the alum-treated and control litter, respectively, indicating a 78% reduction of P runoff. Overall, SRP concentrations in runoff water were reduced 73% with alum-treated litter during the 3 yr of monitoring.

In Fig. 5 and 6, the average P concentrations in runoff water are plotted as a function of time. Note that discrete samples were collected from each runoff event, as described in the Materials and Methods section, and analyzed separately. The water samplers used for this study could collect up to 24 samples for any given runoff event. An example of the SRP concentrations collected for individual samples is shown in Fig. 7. These data indicate that P concentrations do not change much during a runoff event.

The mechanism of action of alum with respect to reducing P solubility is unclear. Aluminum from alum may be transformed to $Al(OH)_3$ in the litter, which adsorbs P. With time, an amorphous aluminum phosphate mineral could form. Alternatively, an amorphous aluminum phosphate may form immediately. Jaynes et al. (1999) were unable to detect crystalline aluminum phosphate compounds in alum-treated litter using x-ray diffraction and thermal analyses. However, ion activity product calculations indicate that alum-treated litter is supersaturated with respect to variscite, indicating that it may be forming (Jaynes et al., 1999). Regardless of which mechanism is operating, the net result will be a decrease in P solubility with time. Shreve et al. (1996) found soluble P decreased with time in soils fertilized with alum-treated litter. Data from a long-term study being conducted on small plots indicates that soil test P levels are significantly lower when alum-treated litter is used, rather than normal litter (Self-Davis et al., 1998).

## Runoff Water pH and Aluminum Content

The pH of the runoff water before litter application was 6.25 (Fig. 8A, Table 4). Following litter application,

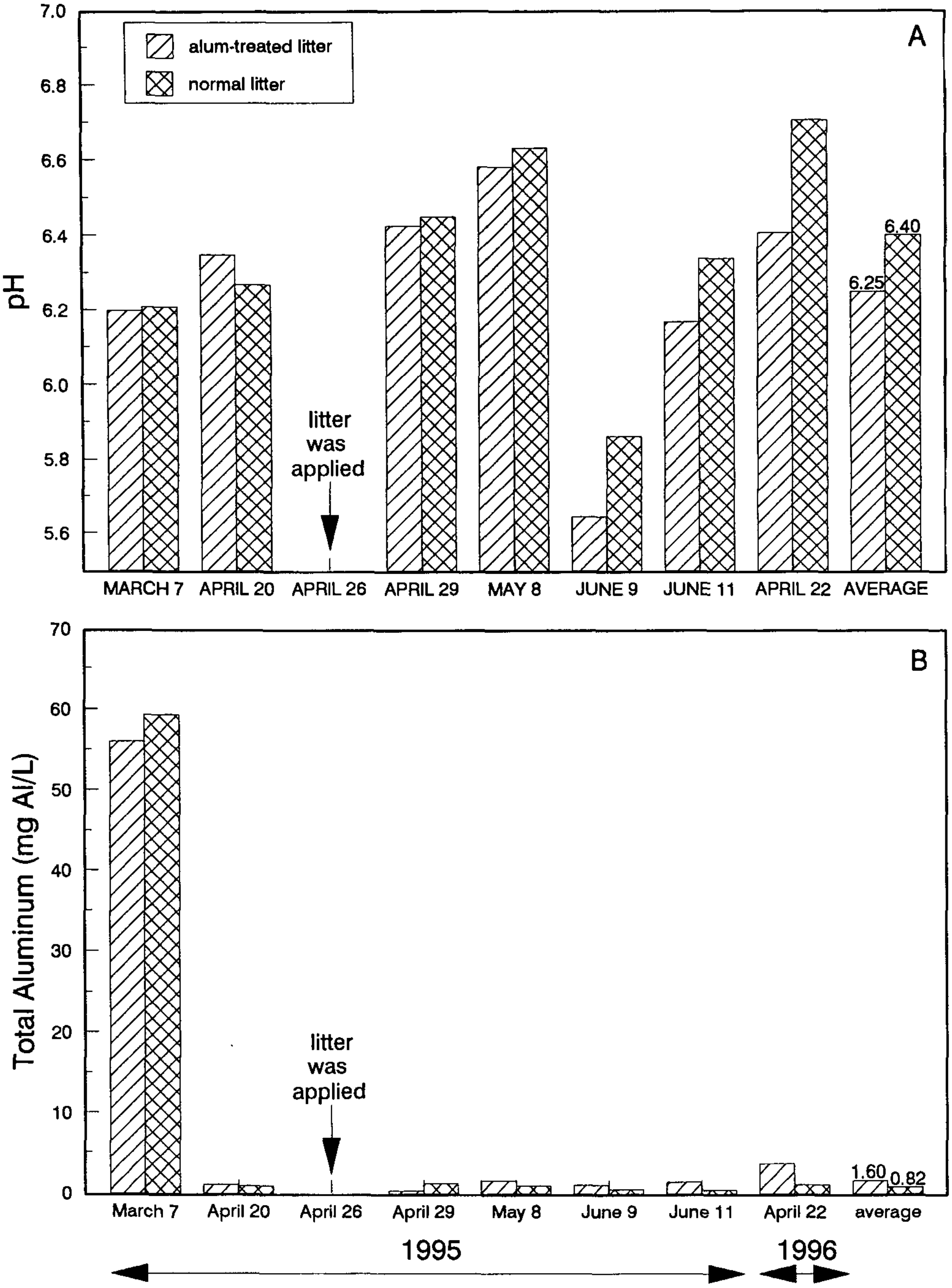

Fig. 8. Effect of alum-treated and normal litter on runoff water (*A*) pH, and (*B*) total aluminum.

the pH initially increased in late April and early May 1995, then decreased in early June (Fig. 8A). The pH of the runoff water from normal litter tended to be higher for the first year than that from alum-treated litter (6.40 vs. 6.25), however, they were not significantly different. This trend was expected, since the pH of alum-treated litter was somewhat lower than normal litter.

In a long-term small plot study on the effects of poultry litter on soil chemical properties, Moore et al. (1998a) showed that both alum-treated litter and normal poultry litter increased soil pH with time, although the increases were greater for normal litter. These findings indicate that the liming capacity of these manures exceed the potential acidity formed during nitrification of $NH_4$–N. In the same study, Moore et al. (1998a) found that $NH_4NO_3$, the most common inorganic N fertilizer in the USA, actually reduced soil pH, resulting in exchangeable Al concentrations in the soil that were five times higher than that in soils fertilized with normal or alum-treated litter.

Aluminum contents in soils vary from 1 to 30%, with average soils in the USA containing about 7% (Lindsay, 1979). The Al content of alum-treated litter is 1 to 2%. Hence, it would take 200 to 400 yr to increase the total Al content in a hectare furrow slice from 7 to 8%. Even then, only the total Al would increase. Since alum-

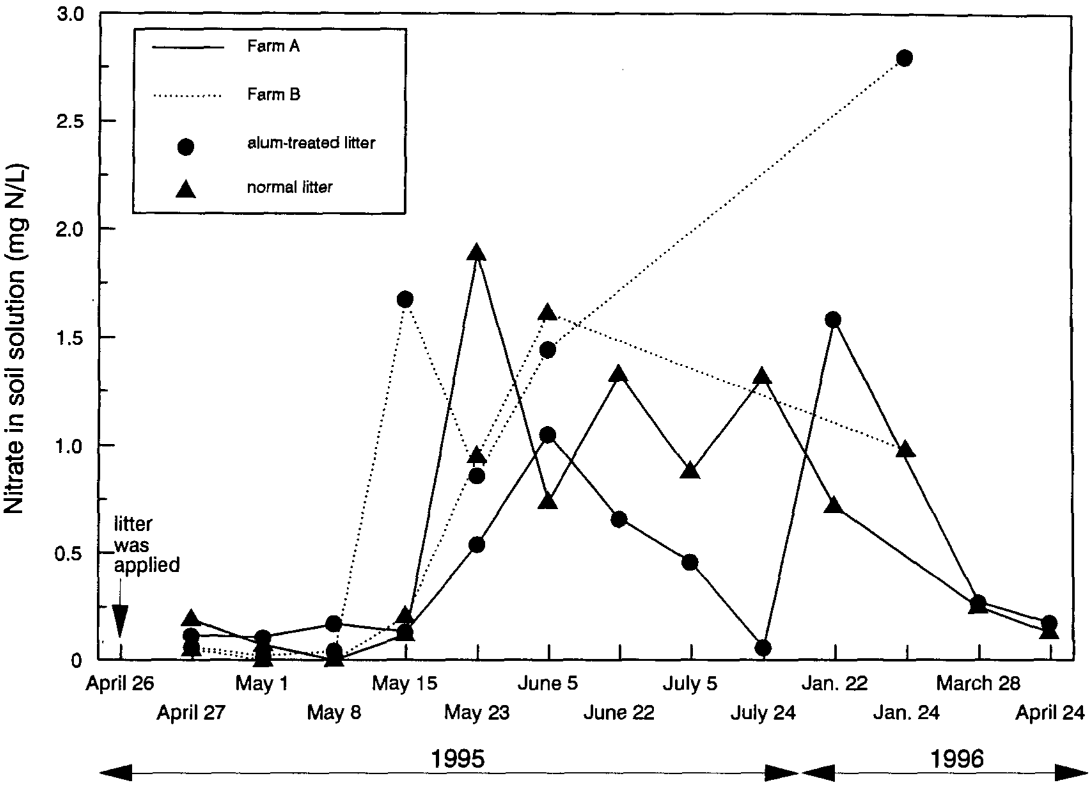

Fig. 9. Nitrate concentrations in soil solution from fields fertilized with alum-treated and normal poultry litter as a function of time.

treated litter has been shown to increase soil pH (Moore et al., 1998a), the soluble Al would probably decrease, since Al solubility is closely regulated by soil pH.

A substantial amount of soil erosion occurred during the first runoff event after the flumes had been installed, resulting in high concentrations of total Al in the runoff (Fig. 8B). This was before any fertilization with alum-treated or normal litter. However, once the flumes had weathered in, very little Al was in the runoff. It should be noted that all of the Al from the alum would be either $Al(OH)_3$ or $AlPO_4$, since the pH of the litter is around 7.5 at the end of the growout and would not be expected to contribute to Al runoff, since these forms are not soluble. Therefore, it is not surprising that there was no significant difference in Al runoff between normal and alum-treated litter. Likewise, soluble Al concentrations in runoff were unaffected by litter type (Table 6). These data correspond to data reported by Moore et al. (1998b), who showed soluble Al concentrations in runoff water were unaffected by litter type. Long-term studies being conducted on small plots have also shown that alum-treated litter does not affect aluminum uptake by plants (Moore et al., 1998a).

Soluble reactive P and TP were the only two parameters studied that were significantly affected by litter type (Tables 6 and 7). This is contrary to results reported by Moore et al. (1998b), who showed concentrations of heavy metals (As, Cu, Fe, and Zn) were significantly lower in runoff from alum-treated litter compared with normal litter. Major differences in the two studies that may have caused this: The study by Moore et al. (1998b) was a small-plot study, where rainfall simulators were used to produce a 5 cm/hr rainfall event immediately after litter application and 7 d later. This is a worst-case scenario and resulted in heavy metal concentrations far higher than those observed in this study.

## Nitrate Leaching

Soil $NO_3$–N levels were relatively low at both farms for both the watersheds fertilized with alum-treated and normal litter (Fig. 9). Normally the $NO_3$–N levels were below 2 mg $NO_3$–N/kg soil, except for the samples taken on 29 Apr. 1996, when a few higher values were noted. There were no significant differences in soil $NO_3$–N levels between alum-treated and normal litter. Soil solution $NO_3$–N concentrations followed the same trends as the soil $NO_3$–N values, with most concentrations below 2 mg $NO_3$–N/L (data not shown). Soil solution $NO_3$–N levels were very low before and immediately following litter application; however, about 3 wk after litter application the values increased to around 1.5 mg $NO_3$–N/L. The highest soil solution $NO_3$–N values observed was 2.8 mg $NO_3$–N/L. The mean $NO_3$–N for the alum-treated and normal litter were 0.45 and 0.64 mg $NO_3$–N/L for Farm A and 0.99 and 0.54 mg $NO_3$–N for Farm B. There were no significant differences in soil solution $NO_3$–N levels because of the type of litter. These $NO_3$–N levels are far below the 10 mg $NO_3$–N standard for drinking water, indicating $NO_3$–N leaching was not a problem under the conditions of this study.

Alum-treated litter has been shown to increase tall fescue yields because of increased N availability (Shreve et al., 1995). The alum-treated litter had a higher N content than normal litter (Table 3). This higher N content translated to 18 kg N/ha more N for the first year in the fields fertilized with alum-treated litter than normal litter. However, lysimeter and soil data indicate the amount of $NO_3$–N leaching was not significantly affected by alum-treated litter.

## CONCLUSIONS

Alum applications to litter in broiler houses resulted in lower litter pH, which resulted in significant reductions in atmospheric $NH_3$. Ammonia fluxes were reduced by 99% by alum for the first 4 wk of the growout. Lower $NH_3$ levels resulted in significantly heavier birds in houses treated with alum than the controls (1.66 kg for control birds and 1.73 kg for birds grown on alum-treated litter). Soluble reactive P concentrations were 73% lower in runoff water from alum-treated litter, compared with normal litter for a 3-yr period. Total P runoff followed the same trends. Aluminum runoff and $NO_3$ leaching were not affected by alum. These data indicate that using alum to treat poultry litter enhanced poultry production and reduced the negative impact of this important resource on water quality.

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