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Article

Factors Influencing Ammonia Concentrations above Corn Fields after Dairy Manure Application

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Abstract: (206): Ammonia-nitrogen (NH_3 -N) loss from agriculture decreases crop yield potential and environmental quality. Incorporating animal manures by chisel plowing (CP) can reduce NH_3 loss but may increase erosion and compaction potential compared to lower disturbance methods. Vertical tillage (VT) is designed to reduce disturbance and conserve more crop residue than CP, however its effect on NH_3 loss from manure application is largely unknown. Six trials in corn production systems were conducted to evaluate the impacts of manure incorporation method (CP, VT, or broadcast) and weather conditions on NH_3-N concentrations during 2013 to 2016 at a research farm in central Wisconsin, USA. Passive samplers were used to measure NH_3-N concentrations at 30-cm above the ground during the first 0 to 24 and 24 to 48 hr post-application/incorporation. Average NH_3 -N concentrations for CP and VT were 44 to 86% of surface broadcast and similar for most trials, while crop residue coverage was greater for VT than CP (39 and 22% of control plots, respectively). Concentrations of NH_3 -N were correlated with the amount of plot area covered by manure for the first ($r = 0.56$, $P<0.0001$) and second measurement periods ($r = 0.85$, $P<0.0001$). Results show that VT had comparable NH_3-N concentration reductions to CP while conserving more crop residue.

Keywords: agriculture; ammonia; liquid diary manure; nitrogen; vertical tillage; volatilization

1. Introduction

Dairy manure is a common farm nitrogen (N) source, however, large quantities of ammonia (NH_3) are easily lost during surface application if not mechanically incorporated into the soil [1–4]. Volatilization of NH_3-N from manure and fertilizers represents a lost source of potentially available crop N and can contribute to deleterious impacts on air and nearby surface water quality [1–3]. In reviewing nitrous oxide and NH_3 emission studies, Webb et al. [4] reported that immediate manure incorporation by moldboard plowing was the most effective method (≥ 90%)to reduce NH_3 losses.

Other studies indicate that NH_3 loss associated with manure application can vary widely (40 to 95%) depending on specific tillage implements and other site-specific factors (manure type, soils, weather) [5–10]. Low-disturbance methods including shallow disc injection and band application/aeration may also be effective, with shallow disc injection generally more effective on reducing soluble N and phosphorus concentrations in surface runoff [6,7,11–13]. Huijsmans et al. [6] summarized studies from the Netherlands and determined that surface incorporation by various tillage methods and injection reduced NH_3 volatilization compared to surface application by 75 and 95% on average, respectively. The time between manure application and incorporation is critical, since 24 to 39% of NH_3 volatilization can occur within the first 60 minutes of application [14,15]. Huijsmans et al. [16] measured a 70% loss of NH_4-N applied in the first 3 hours after manure application. A potential drawback of conventional tillage manure incorporation is enhanced erosion potential and less crop residue compared to lower disturbance methods or surface application [17–19].

Cropping system factors including crop type/stage of growth along with quantity and type of crop residue can also impact NH_3 loss after manure application. Surface manure application on bare ground without any incorporation tends to result in lower NH_3 volatilization compared to losses on fields with a standing crop, stubble, or substantial residues. Crop residues expose manure to more air flow which can exacerbate NH_3 emission, particularly with drier manure (lower dry matter solids) as less infiltrates into the soil [14,20]. Soil conditions also impact NH_3 losses via interactions on turbulent diffusion of NH_3 from the manure surface and lateral transport, in addition to impacts on manure infiltration rates and surface roughness, which affect NH_3 losses [21]. Weather conditions also affect NH_3 loss [22–25]. Wind speed aids in the upward and sideways transport of NH_3 [14,15,24], although the effect of wind speed may not be a factor if manure incorporation occurs [26].

A main goal of reduced tillage is to decrease soil erosion and maintain crop residue for soil quality benefits, however reduced fuel and labor costs may also be realized [27–34]. In 2008, over 46 million ha (41.5% of cropland) in the US used some form of re-duced/conservation tillage [27]. Vertical tillage (VT) is a reduced tillage method by which coulters/tines enter the soil on a vertical plane, minimizing shear force and sur-face disturbance. Implements for VT encompass a wide range of designs with various settings for soil and residue incorporation levels [27,34] and are operated at shallow depths (7.5 to 10 cm) and higher speeds than traditional tillage implements [27]. While some VT research has addressed residue levels [34], there is a lack of published research on using VT to incorporate manure and reduce the risk of NH_3 loss compared to more traditional tillage like chisel plowing (CP). Here, we evaluated the impact of CP and VT on average NH_3 concentrations immediately above the soil compared to no manure controls and surface application/broadcast (without any incorporation) in an upper Midwest corn production system. Crop residue/manure coverage and weather conditions were also monitored for each trial as additional covariates.

2. Materials and Methods

Six separate field experiments were conducted during 2013 to 2016 and included a range of crop residue and manure characteristics (Table 1). All trials were performed at the University of Wisconsin (WI)/USDA-ARS Marshfield Agricultural Research Station in Stratford, WI, USA on a somewhat poorly drained Withee silt loam soil (fine-loamy, mixed, superactive, frigid Aquic Glossudalfs; 0-2% slope). Plots were established on active crop production fields used for forage production including corn (*Zea mays* L.) harvested for silage, corn harvested for grain, or small grain (*Avena sativa* L.). Each of the six trials was arranged in a randomized complete block design with 3 blocks and 4 treatments consisting of manure incorporated via CP or VT, surface broadcast application (no incorporation), and a no manure control. Plots were approximately 9 by 24 m for trial 1 and 2 and 15.3 by 15.3 m for trials 3 through 6 to accommodate tillage and manure application equipment (3 to 7.5 m in between plots within a block depending on field size with ≥ 30.5 m between blocks). Blocks were set up perpendicular to prevailing wind direction to reduce NH_3 transport among plots. Four of the VT trials were performed with one VT implement (Case IH 330, Turbo, Racine, WI) while a different tool (Great Plains Turbo-Till 1800, Aberdeen, WI) was used for the last two trials (Table 1). VT implements were set to run between 5 and 8 cm deep. Chisel plow tillage (Case IH Brillion, WI) was done at 15 cm deep and moved more soil compared to VT. All tillage incorporation occurred within 5 minutes of dairy manure application. Manure was applied using either a box type spreader for semi-solid manure (H&S HP425, Marshfield, WI) or a discharge spreader for liquid manure (Calumet 5000, Indianapolis, IN). Manure application target rates were 84,000 L ha^{-1} for liquid and 90 Mg ha^{-1} for solid manure. Manure was sampled directly from spreaders (3 per block/trial) and analyzed for dry matter/solids content, total nitrogen (TN), total phosphorus, and ammonium-N contents (NH_4-N) by the University of Wisconsin Soil and Forage Laboratory (Marshfield, WI) [35]. Spreaders were calibrated by applying manure over plastic sheets or weighing manure spreaders empty and full to compute applied dry matter manure mass (Table 2).

Table 1. Trial dates, equipment, residue and manure type used for the study.

Trial	Date	Treatments					Residue	Manure Type
		Control	Surface	Chisel	Case IH 330	Great Plains Turbo Max 1800		
1	9/25/2013	X	X		X		Silage Corn	Solid Pack
2	7/2/2014	X	X	X	X		Oats	Separated Liquid
3	8/11/2015	X	X	X	X		Oats	Unagitated Separated Liquid
4	11/4/2015	X	X		X		Grain Corn	Whole Dairy Slurry
5	5/3/2016	X	X	X		X	Grain Corn	Whole Dairy Slurry
6	5/17/2016	X	X	X		X	Silage Corn	Whole Dairy Slurry

Table 2. Manure composition and nutrients applied for each trial.

Trial	Date	DM †	TN	TP	NH_4-N	pH	Rate‡	TN	TP	NH_4-N
			%				Mg ha^{-1}		kg ha^{-1}	
1	9/25/2013	29 ±0.9†‡	1.8 ±0.06	0.34 ±0.04	0.4 ±0.1	8.3 ±0.12	95.3	484	91	94
2	7/2/2014	1.5 ±0.05	6.8 ±0.20	1.09 ±0.00	4.5 ±0.2	7.6 ±0.05	53.6	82	13	54
3	8/11/2015	5.1 ±0.1	3.3 ±0.05	0.65 ±0.03	1.3 ±0.0	8.2 ±0.08	83.9	137	28	55
4	11/4/2015	22 ±1.8	1.6 ±0.15	0.30 ±0.00	0.7 ±0.1	8.1 ±0.05	110	412	80	185
5	5/3/2016	8.7 ±0.60	3.1 ±0.25	0.74 ±0.00	1.5 ±0.1	7.8 ±0.10	69.6	181	44	89
6	5/17/2016	6.5 ±0.1	3.1 ±0.08	0.79 ±0.01	1.3 ±0.05	7.8 ±0.20	90.9	180	46	74

† DM = dry matter, TN = total nitrogen, TP = total phosphorus, NH4-N = ammonium-nitrogen. ‡ Rate = manure nutrient application rate = nutrient content x manure application rate. †‡ One standard deviation from the mean

Soil samples were collected from control plots at each trial to provide a general evaluation of soil fertility across experimental blocks prior to manure application. Five individual sample cores (2.5 cm diameter auger taken from 0 to 20 cm depth) per plot were composited. Air dried, ground (2 mm) samples were analyzed for organic matter contents by loss on ignition [35,36], pH by electrometric method 1:1 soil:water [36], and NH_4-N by flow injection analysis of a 2 M KCl extract [37] by the University of Wisconsin Soil and Forage Lab (Marshfield, WI). Soil moisture measurements were also performed (Delta-T Devices Theta Probe, Burwell/Cambridge, UK) by averaging 3 to 5 individual measurements per control plot. A portable weather station (Spectrum Watchdog 2000 series, Aurora, IL USA) was positioned at the field edge to determine temperature, humidity, wind speed and rainfall (accuracy ±2°C, ±2% RH, ±3 km h^{-1}, ±2%, respectively) during each trial. For trials in 2015 and 2016 (n = 4), the plot area covered by either manure or crop residue was estimated (at 1.5 m above plot surface, 2.25 m^2/plot) using digital plot images (SamplePoint software) [38].

Ammonia concentrations were measured using passive samplers (Ogawa USA Inc., Pompano Beach, Fl.) and consisted of a Teflon cylinder with separate ends containing an acidified filter paper (NH_3 sink) behind a metal screen and diffusion barrier. These samplers can accurately measure NH_3 concentrations over a wide range of concentrations (1 µg NH_3-N m^{-3} to 10 mg NH_3-N m^{-3}). The reported sampler NH_3 diffusion coefficient is 0.232 cm^2 s^{-1} with a detection limit of 3.7 µg NH_3-N m^{-3} for a 24-hour period (uncertainty of ±5%) [39]. Roadman et al. [39] provide additional background and validation data for the samplers. Immediately after manure application and incorporation via VT or CP, three stakes per plot were secured in the ground on a diagonal line across each plot centered within the 6 m by 6 m center area. Sampling units were then attached to stakes positioned at 30.5 cm above the ground surface (Figure 1). Samplers were attached to the stakes on mounts below PVC shelter caps. Average NH_3 concentration of the three samplers per plot was used for data analysis for each of the six trials. Additional samplers were positioned upwind to measure background NH_3. Samplers were deployed immediately after manure application and retrieved for analysis at 24 hr. Samplers collected at 24 hr were then replaced with new samplers and collected again after 24 hr (48 hr after manure application). Field blanks were individual samplers kept in air-tight containers in the field during sampler deployment, transport, and analysis (laboratory blanks were kept in air-tight containers in the lab during sampler preparation and analysis). All blanks were

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below the method detection limit (0.005 mg N L^{-1} as NH_3) except the first 24-hour field blank for 17 May 2016 (0.006 mg N L^{-1} as NH_3). The NH_3 traps inside samplers were taken back to the laboratory and extracted with 8 mL of deionized water and NH_3-N was determined by flow injection analysis [40]. Average ambient concentration of NH_3-N for the 24 hr deployment period was determined after Roadman et al. [39].

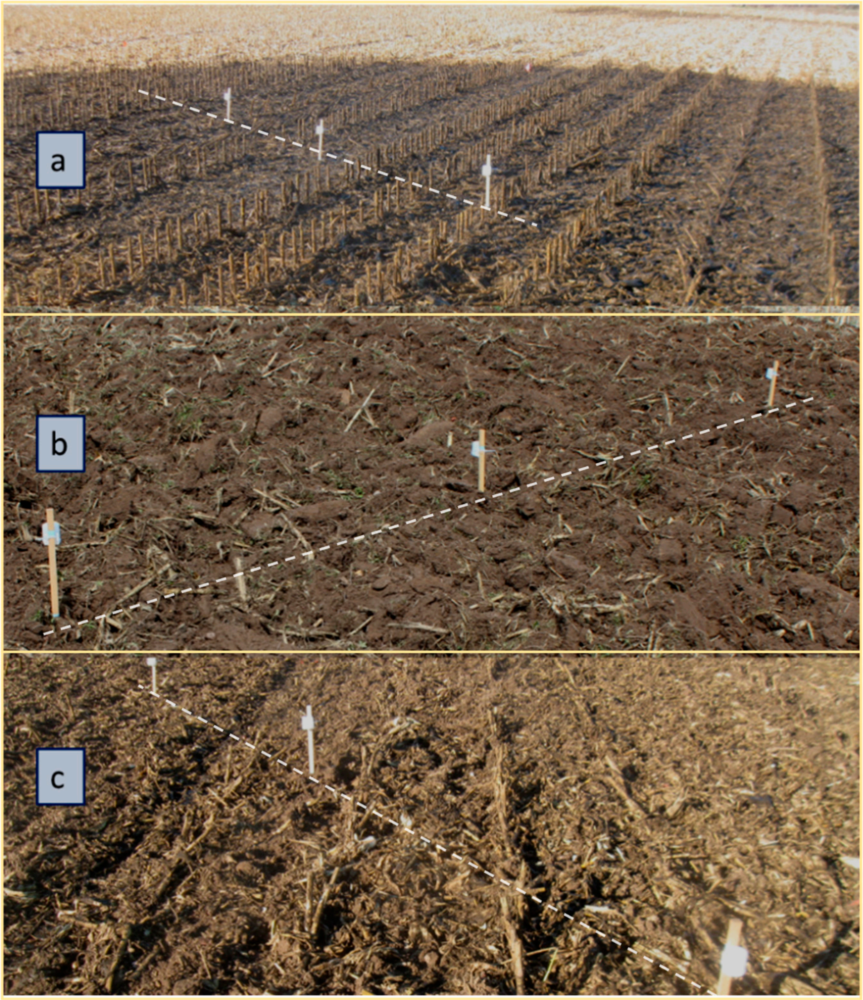

Figure 1. Photographs of experimental setup and manure-tillage treatments established in a corn field previously harvested for grain at the research site (Trial 5). Images show the surface/broadcast application without any incorporation (**a**), manure incorporation by chisel plowing (CP) (**b**), and manure incorporation by vertical tillage (VT) (**c**). Dashed white lines show the location of the three samplers directly above the soil surface. .

Average NH_3-N concentrations for each treatment for the first- and second-time sampling periods were subjected to analysis of variance using the general linear modeling procedure (proc glm) of the Statistical Analysis System [41] under the assumption that the variability among application/incorporation treatment samplers would far exceed minor differences in soil properties (Table 3). Each trial was analyzed as an individual experiment. Data were transformed as necessary (log_{10} or square root) to achieve normality and homogeneity of variance. Treatment means were separated by Fisher's protected LSD ($P \leq 0.10$). Pearson correlation coefficients (proc corr) were also computed between NH_3 concentrations, select weather conditions for the day of the trials and percent residue/ manure coverage from the plot image analysis data.

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Table 3. Average background soil properties for each trial.

Trial	Date	pH	NH_4-N †	Moisture	OM ‡
			mg kg^{-1}	g kg^{-1}	
1	9/25/2013	7.2 ±0.05	. †‡	184 ±2.4	27 ±1.7
2	7/2/2014	7.0 ±0.16	3.7 ±1.5	329 ±26	32 ±1.4
3	8/11/2015	7.0 ±0.08	3.2 ±0.8	317 ±17	30 ±3.4
4	11/4/2015	6.3 ±0.20	2.6 ±0.8	346 ±19	30 ±0.5
5	5/3/2016	6.8 ±0.12	3.4 ±0.2	401 ±38	33 ±0.8
6	5/17/2016	6.7 ±0.05	3.7 ±1.2	289 ±6.2	35 ±0.5

†Plant-available soil ammonium-nitrogen concentration. ‡ Soil organic matter content, †‡ Not measured for the trial. ‡† One standard deviation from the mean.

3. Results and Discussion

3.1. Manure and Soil Properties

Manure dry matter solids content, total N, total P and NH_4-N inputs varied among individual experiments (Table 2) and therefore influenced how close to the target application rate manure was applied. Manure for Trials 1 and 4 had higher dry matter solids content compared to other trials, resulting in correspondingly larger total N and NH_4-N application (Table 2). Background soil fertility in control plots was similar among experimental trial plots, with pH and organic matter contents averaging 6.7 ± 0.5 and 31 ± 5 g kg^{-1} (Table 3). Average soil moisture contents at the time of each experiment were similar and close to field capacity for Trials 2, 3, 4, and 6; Trial 1 was done under drier soil conditions and Trial 5 was in wetter conditions (Table 3).

3.2. Influnece of Manure Incorporation on NH_3-N Concentrations

Mean NH_3 concentrations ranged from <0.7 mg NH_3-N m^{-3} (7 μg NH_3-N m^{-3}) to < 0.1 mg NH_3-N m^{-3} in surface applied manure plots for the first 24-hr monitoring period across trials (Figure 2). Compared to the first 24-hr monitoring period, NH_3-N concentrations consistently and substantially decreased (by up to an order of magnitude) for the 24 to 48 hr period across treatments (Figure 2). Maximum NH_3-N concentrations for the surface applied manure treatment were well below European guidelines for occupational health exposure (≤ 22 mg NH_3-N m^{-3} for 10 min or ≤ 16 mg NH_3-N m^{-3} for 8 hr) [42,43]. Background NH_3-N concentrations in agricultural areas have been reported in the range of <0.1 to 1.5 mg NH_3-N m^{-3} [42–44] and are in the range of control plot NH_3-N concentrations measured in our trials.

Our results support previous studies indicating the importance of using some type of incorporation to decrease NH_3 loss potential from manure applications. Manure incorporation consistently and significantly reduced NH_3 concentrations from surface application levels during the first 24 hr after application and in 5 of 6 trials for the second 24-hour period. Mean VT NH_3-N concentrations did not differ from CP for all but one trial in the first 24 hours. In a four-year study from South Central WI, Powell et al [8] demonstrated that liquid dairy manure injected into the soil of corn production systems was much less vulnerable to NH_3 volatilization losses compared to surface broadcast application, supporting our findings here that incorporation decreased NH_3 concentrations. They showed surface applied manure had 1.9- and 4.3-fold greater NH_3-N concentrations compared to incorporation (soil aeration or injection). In a recent low-disturbance manure study, Sherman et al. [12] showed that 35.5% of manure applied NH_4-N for a corn silage system was lost as NH_3 emissions, as compared to 0.11 and 4.5% with strip-till injection or shallow disc injection, respectively. These studies demonstrate the importance of adequate incorporation and manure-to-soil contact for capturing more total ammoniacal N (NH_3 + NH_4^+) from manure applications and reducing NH_3 emissions.

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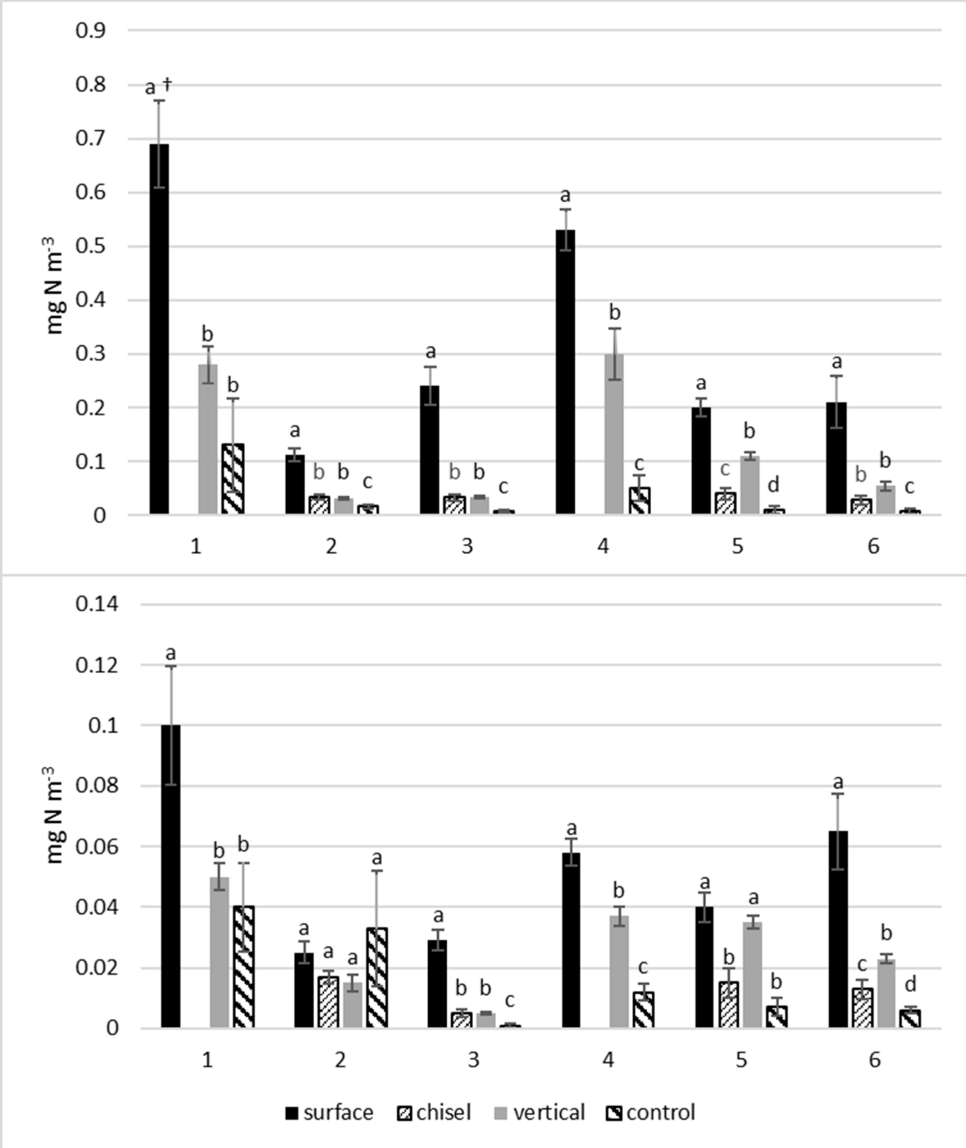

Figure 2. Average ammonia–nitrogen (NH_3-N) concentration for each treatment and trial during the first 24 h (top) and second 24 h (bottom, note different y-axis scale) after application. † bars with the same letter within a trial date and time period do not differ at $P \leq 0.1$.

3.3. Impact of Weather Conditions and Manure on NH_3-N Concentrations

Control plots in our trials generally had lower NH_3-N concentrations, however they were not always significantly lower than manure treatments. For example, mean control plot NH_3-N concentrations for trial l (both sampling periods) and trial 2 (24 to 48 hr only) did not differ ($P \geq 0.10$) from VT concentrations. It is possible that some amount of volatilized NH_3-N from manure plots in our trials was transported to down-wind samplers including controls, thus confounding treatment effects. Potential NH_3 transport from above manure plots downwind to other plots is more likely with weather conditions favoring NH_3 emission (trial 1 and on the second day of trial 2 in our study) as warmer, windier conditions are known to increase NH_3 losses [43–45]. While no manure was applied within 30 m blocks in an effort to reduce NH_3 transport, this was likely insufficient in preventing all NH_3 transfer from manured to control plots under all weather conditions. Consistent patterns of significantly lower NH_3 concentrations for control plots in all other trials suggest that carryover was not an issue for most trials.

Adequately controlling NH_3 emissions with management is difficult, since NH_3 is easily transported and depends dynamically on several interrelated soil-ambient air exchange processes and related equilibria [43,44]. In our study, weather conditions for trial 1 were more conducive to NH_3 volatilization with the higher wind speeds and gusts compared to other trial dates (Table 4) and may help to explain the higher NH_3-N concentration measured for the control plots for trial 1. Moreover, NH_3-N concentrations were significantly correlated with relative humidity (first 24 hours), wind speed, and wind gusts (both time periods) across trials (Table 4). Other studies have reported significant correlations between NH_3 emission and meteorological variables (wind speed, gust speed, humidity, solar radiation) for agricultural sectors [14,15,22,24]. While relationships among NH_3-N concentrations and weather factors captured by our study were not particularly strong, their significance indicates they were important covariates affecting NH_3-N concentrations over a range of field conditions.

Table 4. Select meteorological variables for trial dates and Pearson correlation coefficients for relationship to NH_3-N concentrations across trials.

Trial	Date	Relative Humidity	Temperature	Total Rainfall	Wind Speed	Wind Gusts
		%	°C	mm	m s^{-1}	
1	9/25/2013	89	13.9	0.0	2.55	7.38
2	7/2/2014	60	16.4	0.0	1.31	3.21
3	8/11/2015	73	20.0	0.0	0.93	2.30
4	11/4/2015	85	14.1	8.4	2.80	5.19
5	5/3/2016	62	9.40	7.1	2.03	4.19
6	5/17/2016	52	11.1	1.3	0.43	1.69
		Pearson Correlation Coefficients				
	first 24 h	0.55 **	-0.51	0.13	0.49 *	0.56 **
	second 24 h	0.39	-0.27	0.10	0.43 *	0.55 **

* Significant at $P \leq 0.05$. **Significant at $P \leq 0.01$.

Another limitation of our study was the relatively large time windows over which samplers were deployed yielding an average NH_3 concentration over that period. Due to sampler detection limits and the relatively low NH_3 concentrations in our setting, longer deployment times were required [39]). In addition, parameters needed for air flux estimates were not measured primarily due to time constraints, which may have limited our ability to discriminate among treatments. However, since soil variation was low among plots (Table 2) compared to the large NH_3 concentration differences caused by manure-tillage treatments, we assume the NH_3 concentration differences would be proportional to fluxes. Miola et al. [46] cautioned that passive sampling tends to underestimate NH_3 concentrations compared to dynamic chamber and other methods, however deploying passive samplers immediately after manure application can help offset underestimation of NH_3-N [39,46].

3.4. Impact of Crop Residue and Manure Coverage on NH_3-N Concentrations

Estimated crop residue coverage for VT and CP as a percentage of control plot residue coverage was 39 and 22% averaged across the trials, respectively (Figure 3). The VT implement used for Trials 5 and 6 was slightly less aggressive at moving soil and left a higher percentage of manure on the surface, however VT maintained approximately twice the residue coverage compared to CP in those trials (Figure 3). Other studies in Midwestern corn production systems have shown VT depth and soil type can affect residue amounts remaining on the surface after tillage [27,34,45]. The lower starting residue coverage in our trials compared to some other studies is likely related to the fact that fields were used for silage as well as grain production and were field cultivated at least once per year.

While consistently applied across trials, we caution that our residue and manure coverage approach classified residues coated with manure as manure since it could contribute NH_3-N concentrations measured immediately above the soil, which may have underestimated total residue coverage. While residue coverage was not significantly correlated with NH_3-N concentrations, manure coverage was significantly correlated with NH_3-N concentrations for 0 to 24 hr (r = 0.56, P<0.0001) and 24 to 48 hr (r = 0.85, P<0.0001) sampling periods, indicating the importance of adequately incorporating manure into the soil to substantially decrease NH_3 concentrations.

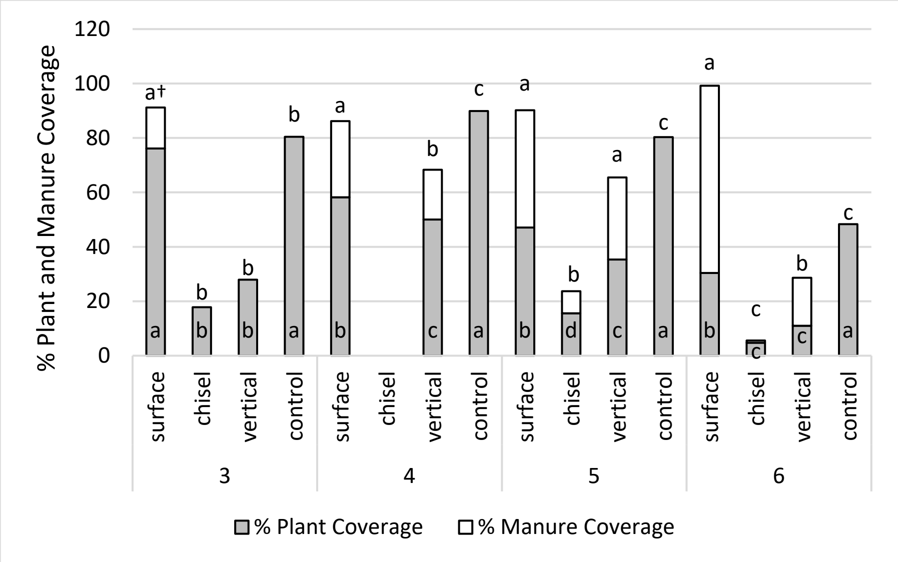

Figure 3. Mean plot area (%) covered by crop residue and/or manure for select trials. †bars with the same letter within a trial date are not significantly different at $P \leq 0.1$. Differences for within trial plant coverage are shown by letters within the gray bar. Differences for within trial manure coverage are shown by letters above the bar.

Additionally, differences in manure types and dry matter solids affect manure's movement into the soil and propensity to remain on crop residue and therefore for NH_3 volatilization losses [20,45,47]. Our results support the idea of a minimum threshold of soil-manure interaction that must be met to substantively reduce NH_3 concentrations from manure applications. Achieving the proper combination of tillage and residue levels requires balancing multiple agronomic considerations and the proper selection and setup of manure application and tillage implements is of critical importance. Overall, our findings highlight the significance of incorporating manure as soon as possible after application to decrease NH_3 loss potential in fields receiving animal manures.

4. Conclusion

Results from our trials indicate that incorporating manure in corn fields with vertical tillage or chisel plowing resulted in similar NH_3-N concentrations measured in the air immediately above soil during the first 24 hours after application despite differences in manure composition and weather conditions. Vertical tillage maintained greater surface coverage of crop residue than chisel plowing**.** Our research highlights the importance of incorporating dairy manure to reduce airborne NH_3-N concentrations as part of an overall strategy to mitigate NH_3-N emission potential from manured agricultural soils. Results also highlight the importance of manure application methods and weather conditions on NH_3-N loss dynamics and stress the need for additional research and development of practical decision support tools to better manage NH_3 in agricultural soils.

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