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Nutrient Losses from Unlined Bedded Swine Hoop Structures and an Associated Windrow Composting Site

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Abstract. *Mass balance analysis of livestock manure management systems can offer important insight into the flows and losses of nutrients and potential pollutants. This study describes the objectives, design, and two years of results from a field study examining the nutrient losses from bedded swine structures and an associated composting site. Nutrient mass balances have been completed on three groups of pigs in naturally ventilated hoop structures, along with the*

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corresponding three composting trials at the outdoor windrow composting site. Soil core nutrient analysis and mass balances on nutrients in the swine production system and composting piles have been used to assess losses to the environment.

The mass balance analysis of deep bedded hoop structures identified significant N losses from the bedded pack (54 ± 6% of the excreted manure; 3.9 kg/pig) but negligible P losses in the hoop. Both N and P losses at the compost site were significant (19 ± 10% and 21 ± 21% of the excreted manure respectively). After losses in both the hoop and the composting process, the nutrient quantities remaining were 1.9 ± 0.4 kg N/pig and 1.0 ± 0.3 kg P/pig.

10% or less of the N losses from the hoop accumulated in the top 1.2 m of soil, and that net accumulation was entirely in the first year. Most N losses within the hoop structure appear to be in gaseous forms, e.g. N_2, N_2O, *and* NH_3. *Improved management of these gaseous losses in bedded livestock systems will be important to making these systems environmentally sustainable.*

Although soil sample variability precluded a direct correlation between nitrogen losses and soil accumulation at the composting site, high apparent soil accumulations did indicate that a considerable fraction of the N losses observed at the composting site are being leaching into the soil. Design and management strategies to mitigate this leaching loss are likely to be necessary for manure composting facilities in humid regions located near vulnerable groundwater resources.

Keywords. Animal housing, deep litter housing, nutrients, manure, composting, mass balance.

Introduction

Livestock facilities and their associated manure management systems are under increasing environmental scrutiny from regulators as well as the public. Concern has broadened in recent years from water quality to odors and other gas emissions, including dust, ammonia, and methane. Engineers and others designing new facilities and developing appropriate compliance strategies has been made more difficult by these multiple criteria, as systems which offer benefits in one area may be detrimental in another. One way of clarifying the nature of these tradeoffs among different livestock and manure systems is through the use of mass balance analysis. By quantifying the different pathways of inputs and outputs from the system, the relative significance of different types of losses can be more readily compared. A mass balance approach can provide important insights for all types of livestock systems, although a complete accounting is more easily achieved in some systems than others.

Although the mechanisms and magnitudes of particular losses from specific components of these systems have been widely investigated (Steele, 1995; Burton, 1997; Hatfield and Stewart, 1998; Miner et al., 2000), only a few researchers have used a mass balance approach to assess total system nutrient flows and losses (Thelosen et al., 1993; Kermarrec et al., 1998). Figure 1 provides a generic illustration of a swine production and manure management system with the typical storages and losses.

Some of the inputs and outputs illustrated in Figure 1 are relatively easily measured, while others are much more difficult to accurately quantify. Feed, livestock, and mortalities can be weighed as they enter and exit the system, and are relatively homogeneous so that available label or reference values for many constituents provide reasonable estimates. For example, the growth equations and nutrition data developed by the National Research Council (1998) and National Pork Producer's Council (1999) can be used to estimate the nitrogen content of swine (Tiquia et al., 2001), and similar relationships are available for other nutrients for a variety of livestock species.

Leaching losses and gaseous emissions are less discrete, fluctuating with time, temperature, wind, precipitation and other variables, and are thus much more difficult to measure. Methods for quantifying leaching losses range from soil cores (SSSA, 1986; Landon et al., 1999; Zhu et al., 2000) to various types of pan, suction, and equilibrium tension lysimeters (Lawes et al., 1882; Landon et al., 1999; Steenhuis et al., 1995; Brandi-Dohrn et al., 1996; Brye et al. 1999), to tile drains (Schwab et al., 1973; Richard and Steenhuis, 1988). Careful experimental design is needed with any of these methods to address the challenges of soil heterogeneity, preferential flow, and complex subsurface hydrology, and measuring phenomena that occur at scales other than that of the sampling device remain somewhat problematic.

Monitoring gas emissions from livestock housing and manure storages is similarly problematic, although several relatively robust methods have been developed to collect such data from mechanically ventilated buildings (Monteny and Erisman, 1998, Aarnink and Wagemans, 1999; Demmers et al., 1999, Phillips et al., 2001). However, most such methods are inadequate to characterize mass fluxes in naturally ventilated or outdoor systems where such losses are compounded by flows that vary in magnitude and direction. Temporary artificial control of airflow, either over small areas using flux chambers or over large areas with larger containments (Asteraki et al., 1997; Sommer and Dahl, 1999), provides one approach to simultaneous measurement of flowrate with concentration for flux calculation. Another promising approach uses trace gases such as CO_2 (Pedersen et al, 1998; Demmers et al., 1999) and SF_6 (Kaharabata et al., 2000) to quantify the dilution air and thus allow a back calculation of other fluxes from simultaneous concentration measurements. Trace gases allow frequent, less disruptive measurements in livestock production facilities, while temporary artificial airflow control has been more commonly used for manure storage, treatment system, and land application measurements.

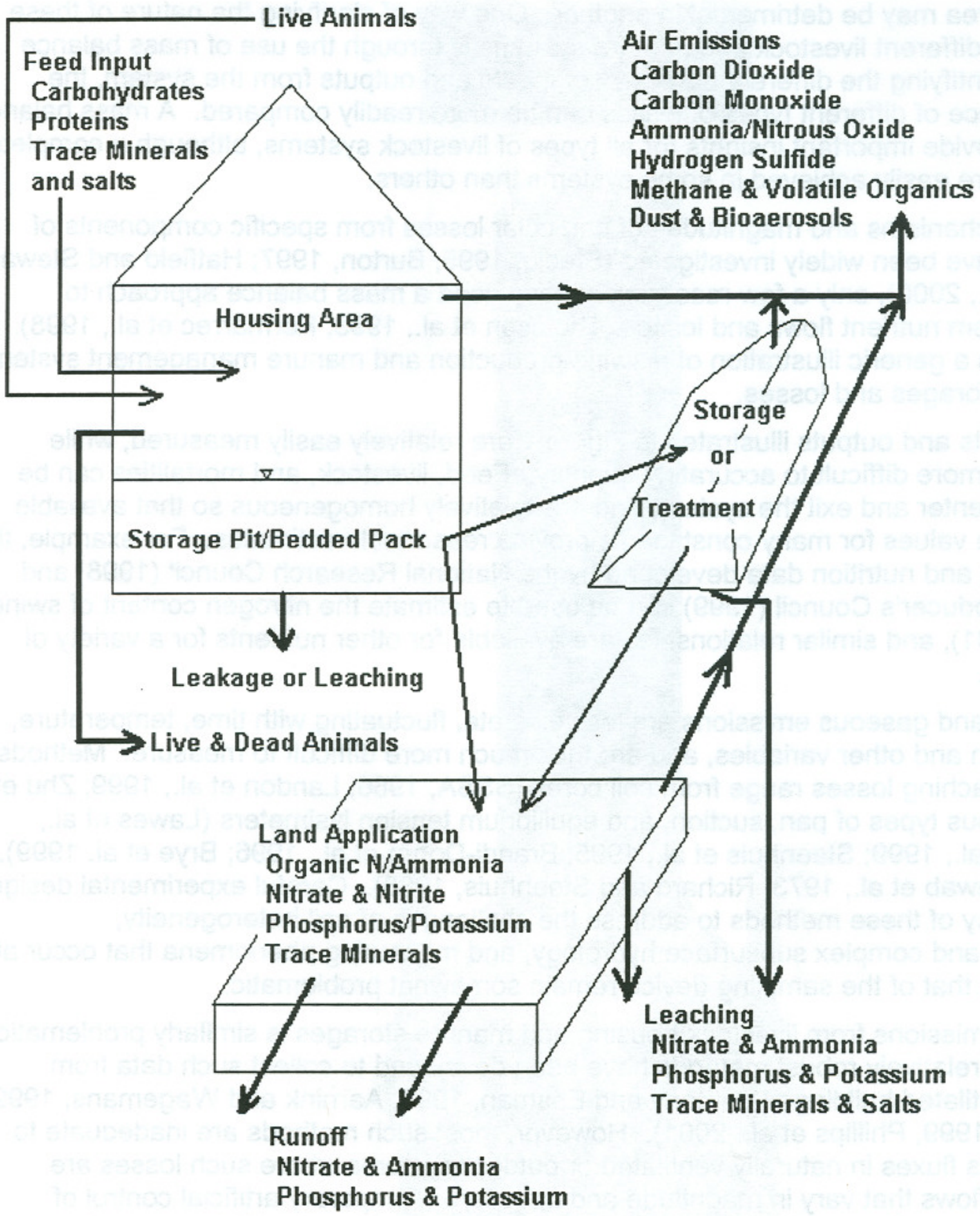

Figure 1. Conceptual schematic of environmentally significant mass flows in a swine production system.

Manure itself can also be a challenge to measure, both because of variability within the manure collection, storage, and treatment system (Lorimor and Kohl, 2000) and because the mass of manure is changing with time. In indoor systems this mass change is primarily from manure additions and evaporation, although in outdoor storages precipitation can also have an effect. With liquid manure handling systems volumetric measurement and evaporation calculations can provide an indication of fluxes if carefully implemented (Glanville et al., 2001). However, because of these total mass changes, changes in concentration do not necessarily correspond to changes in the mass of various constituents, and to the uncritical observer can even seem to imply the opposite of the actual trend. These problems are exacerbated when the manure is decomposing, as is illustrated by the following example from a hypothetical composting system. Neglecting moisture for a moment, if there is a 60% loss in the dry mass, and nitrogen concentrations on a dry basis change from 2 to 3%, the mass of nitrogen in each dry metric ton changes from 20 kg (1000 x 0.02) to 12 kg N (1000 x [1 – 0.60] x 0.03). Despite the 50% increase in N concentration, there was actually a 40% decrease in the mass of N. Moisture adds an additional layer to this analysis, and it is usually changing as well. Because materials are normally weighed on a wet basis (w.b.), and most solid manure analytical results are reported on a dry matter basis (d.b.), moisture content must be measured and incorporated at each step in the analysis. Finally, during initial collection and storage, manure is often being added to the system, so that there are gains as well as losses of moisture, carbon, nutrients, and other constituents.

This report summarizes the initial two years of mass balance analysis of a deep-bedded hoop structure used for swine finishing, as well as the subsequent outdoor windrow composting system. Hoop structures have become widespread in the Midwestern US in recent years and are now found throughout much of North America. This system offers flexible livestock housing at a reduced capital cost relative to conventional confinement structures (Honeyman et al., 1999), and provides animal welfare benefits relative to conventional slatted floor housing (Lay et al., 2000). Animals are housed under a plastic roof supported by semicircular metal hoops, often with a partially raised concrete floor for feeding and watering while most of the floor area is covered with corn stalks or other bedding in an deep-bedded pack. Bedding and manure begin to decompose *in-situ*, providing some supplemental heat in winter (Richard and Smits, 1998), and this decomposition continues through a several month composting process if the manure is piled appropriately when cleaned out of the barn.

Materials and Methods

A mass balance analysis is essentially an accounting procedure, whose results depend on accurate determinations of the individual numbers that make them up. In our analysis we incorporate procedures and conversion factors used in animal science, soil science, and agricultural engineering for the different components of the system. Details of the livestock housing and composting procedures used in this analysis have previously been reported (Tiquia et al., 2000; 2001). In this paper we summarize the overall mass balance analysis, extend it to include two additional hoop production cycles, and report the results from a two year investigation of nutrient leaching into the soil under the bedded pack and composting site. The data presented covers three cycles of finish swine production in the hoops and subsequent composting of the bedded pack. Manure from a total of five hoops is included in the analysis, one in each of the first two cycles and three hoops during the third cycle. Neither the hoops nor the composting site were lined with impermeable layers or otherwise modified from the native soil, other than by vehicular traffic during construction and management of the facility. This facility thus represents a low-cost standard hoop system, with no special efforts at environmental protection.

Livestock, Feed and Bedding

Feed inputs to the system were weighed and standard nutrient concentrations were used to calculate nutrient mass inputs from that source (NRC, 1998). Cornstalk bedding was added to the hoops in a thin layer before each group of feeder pigs arrived, and additional large round bales were added as required during the 4.5 to 5 months each group of pigs was in a hoop. Bales were weighed and samples were analyzed for nutrient content.

Feeder pigs, typically around 23 kg each, were weighed and tagged at the beginning of each production cycle. Each hoop contained about 150 pigs, although there was some variability due to mortalities during the production cycles. Mortalities were weighed when removed from the building, and each finished pig was weighed as it left the hoop for market (averaging approximately 117 kg live weight). These animal weights were multiplied by standard nutrient concentrations for P and K (Mahan and Shields, 1998) and in the case of N also adjusted for carcass weight and fat-free lean index (Ewan, 1998; NRC, 1998; NPPC, 1999).

Manure and Compost

At the time of cleanout each bedded pack was sampled, with a vertical composite sample collected each of 24 locations in a grid. Samples were characterized in the laboratory for a range of constituents (Tiquia et al., 2001). The entire bedded pack was then weighed on portable axle scales before being stacked in windrows for further composting. Composting proceeded in a series of replicated windrow piles, and the compost was again sampled and weighed at the end of each trial (Tiquia et al. 2000; 2001).

Soil Accumulation

An estimate of leaching losses was calculated from the mass accumulations of nutrients in 1.2 meter long soil cores collected at 12 locations (3 positions on 4 transects) under the bedded pack of one of the hoop structures, and an additional 12 locations (4 positions on 3 transects) at the outdoor compost site. Soil sampling occurred in the fall of 1997 (background) as well as the fall of 1998 and 1999. In the later two sampling events the procedure was to clear the compost site for sampling first, then move the bedded pack from a hoop whose pigs had just been marketed to the compost site for a composting trial, and finally to sample the now empty hoop shortly thereafter. Soil samples were extracted with a truck mounted soil sampler and frozen prior to sectioning into 0-15, 15-30, 30-60 and 60-120 cm depths. The soil samples were air-dried prior to being analyzed for total N by combustion at the Iowa State University Soils Testing Laboratory.

Runoff and Gas Emissions

Neither surface runoff nor gas emissions were measured for the production cycles described here. In future studies we hope to collect this data as well so we can close the mass balance analysis with direct measurements rather than indirect estimates.

Results

The following nutrient mass balance results are presented in two sections. First, the N and P losses within the hoop structures and during composting are tabulated. We then examine the nutrient accumulation under the bedded pack and in the soil under the composting site, and compare those accumulations with the observed losses from the manure.

N and P losses within the hoop and during composting

The nutrient accounting procedures for each hoop structure and composting windrow were as previously described (Tiquia et al., 2000; 2001). Records of market pigs, mortalities, and the bedded pack outputs were subtracted from feed consumption, bedding use, and feeder pig inputs to generate N and P losses in the hoop. For each composting windrow, dry matter and nutrient masses were calculated before and after a six week controlled composting process to determine losses during composting. Because farmers using hoop structures have the option to spread manure before or after composting, the dry matter and nutrient masses were also calculated at each of these times. Means and standard deviations for the five hoop structures and subsequent composting trials are indicated in Table 1. Values are reported on a per-pig basis to allow easy comparison with other swine management systems.

Two minor adjustments to these relatively straightforward calculations had to be made to carry the analysis through the composting process on a per-pig basis. Not all the material from each hoop was used for compost windrow construction, so losses during composting were normalized to the proportion of each group of pigs' bedded pack that was composted. Because the site was on soil, some incidental soil was incorporated into the windrows during turning, which for some windrows was quite frequent since that was one of the variables investigated in the composting trials (Tiquia et al., 2000). The amount of soil incorporated was estimated by assuming that the mass of ash in each windrow would have remained constant had there been no soil addition. Observed increases in ash mass at the end of each trial were therefore subtracted from the total windrow dry mass to estimate the dry mass that would have remained without soil incorporation. Nutrients (and organic matter) that may have been incorporated into the composting windrows with the soil were assumed to be negligible.

Table 1. Total Mass, N and P in Hoop Structures and Subsequent Composting.

	Total Mass (kg/pig) (d.b.)	N (kg/pig) (d.b.)	P (kg/pig) (d.b.)
Losses in hoop		3.9 ± 0.6	0.0 ± 0.3
Remaining in bedded pack at cleanout	120.4 ± 46.8	3.3 ± 0.6	1.3 ± 0.4
Losses during composting	30.0 ± 34.8	1.4 ± 0.7	0.3 ± 0.3
Remaining for land application	90.4 ± 15.1	1.9 ± 0.4	1.0 ± 0.3

Total dry matter loss was not calculated within the hoops, although that may be the subject of future analysis. Dry matter losses during composting varied among windrows, but averaged 21 ±15% of the initial dry matter.

Considerable amounts of nitrogen were lost within the hoop structure during the production process, so that by the time the pigs were marketed somewhat more nitrogen had usually been lost than remained in the bedded pack. These losses were 45 ± 11% of the total nitrogen input to the hoops, or 54 ± 6% of the excreted manure N. Nitrogen losses during composting were 19 ± 10% of the original excreted N, or 41 ± 19% of the N remaining at the start of composting.

Particularly heavy N losses were observed during composting trials with a low initial C:N ratio and/or exposed to high precipitation (Tiquia et al., 2000; 2001).

Phosphorus was generally conserved within the hoop structures. Higher losses were observed during the composting process, with losses for individual windrows in the third trial ranging from 20 to 42% of the P measured at the start of composting (Tiquia et al., 2001). On the basis of P originally excreted in the hoop, these composting P losses averaged 21 ± 21%. The high standard deviation relative to the mean reflects the low P losses observed in some of the composting trials.

Soil N accumulations under the bedded pack and composting site

Figures 1 and 2 illustrate the nitrogen concentration profile for the background (1997) and subsequent two years. Mean values are plotted with the standard deviations for all samples at each depth. Large standard deviations for all datasets are an indication of the considerable variability in the samples, which is partly explained by the variable inputs at the surface. In the hoop structure the pigs select dunging and sleeping areas early in each cycle, and maintain that arrangement throughout the tenure of each group. Thus certain regions of the hoop are continuously wetter and more nutrient rich than others for extended periods of time. Similarly, at the compost site the compost piles were turned more or less in place, so there too the high nutrient inputs were concentrated at only a subset of the total area. These high nutrient input locations moved somewhat from cycle to cycle, but not enough during the two years of this trial for any uniformity to reemerge.

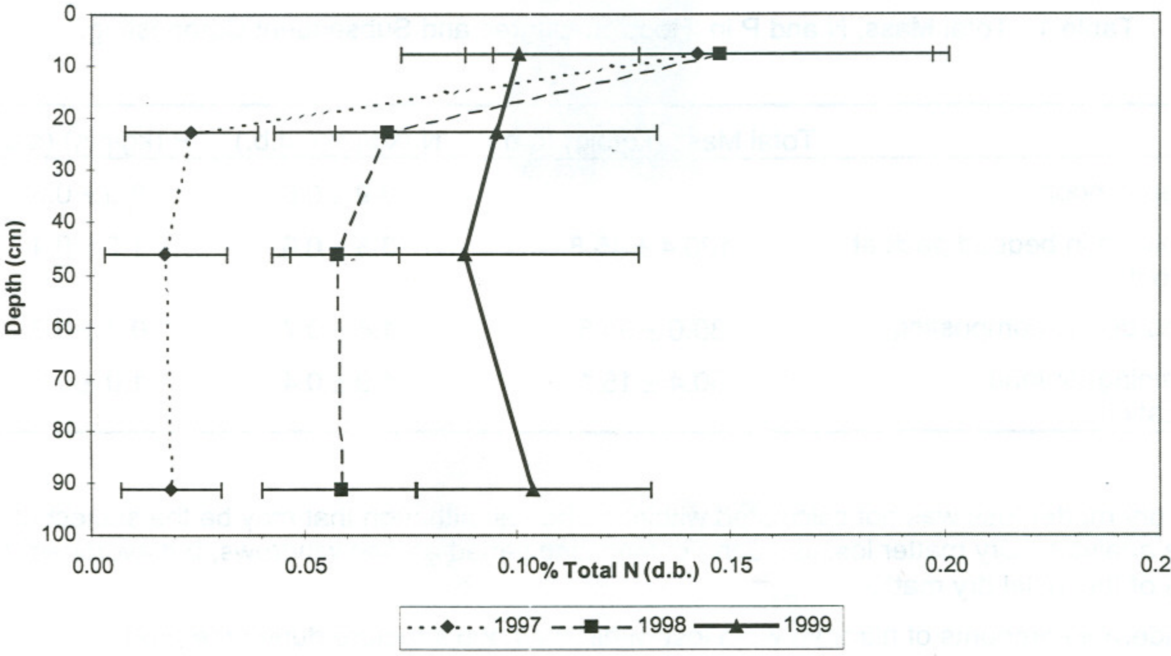

Figure 1. Nitrogen concentrations in the soil profile beneath the outdoor composting site.

Nitrogen accumulation in the soil profile was most significant under the composting site (Figure 1), although accumulations also appeared evident under the bedded pack during the first year and remained at about the same level the following year (Figure 2). At the composting site there is a more pronounced gradient, with higher concentrations at the surface for the background and 1998 samples, but this seems to have diminished by the time of the 1999 sampling. The bedded pack soil profile appears more uniform with depth, although as with the compost site some trends may be masked by the mixing of data from low and high nutrient zones.

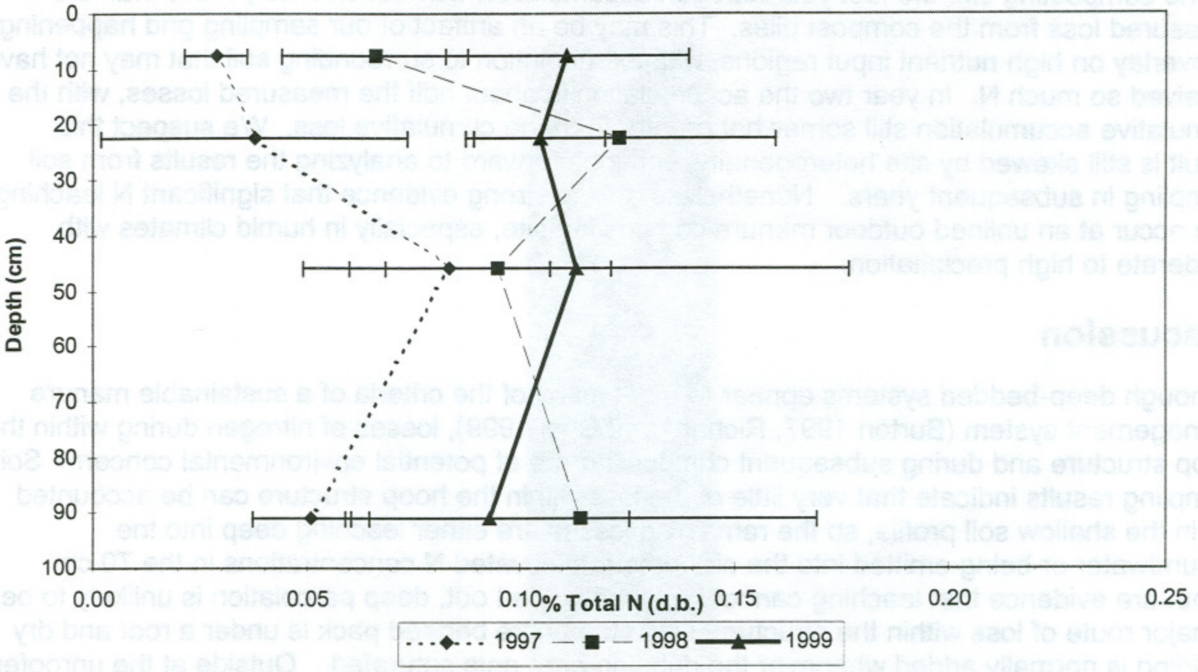

Figure 2. Nitrogen concentrations in the soil profile beneath the covered hoop structure.

Table 2 indicates the incremental nitrogen losses and corresponding soil accumulations under the hoop and composting site. Nitrogen losses were calculated using the mass balance analysis previously described. Soil nutrient concentrations from each core and depth were converted to masses by multiplying by the soil bulk density and the volume of soil each sample represented. The first year losses were from the first two pig production cycles but only the first composting trial, while the remaining pig cycle and composting trials contributed losses in the second year.

Soil accumulation of nitrogen underneath the hoop structure was consistently well below the calculated N losses. During the first year it was about 10% of the total loss, while during the second year their was a slight negative accumulation, indicating that any additional N inputs to the soil were compensated by losses either downward as leaching or upward as a gas.

Table 2. Annual Nitrogen Mass Loss and Soil Accumulation.

	Fall 97 – Fall 98	Fall 98 – Fall 99
Hoop N losses (kg)	1185	1302
Hoop soil accumulation (kg)	120	-6
Compost N losses (kg)	147	467
Compost site accumulation (kg)	453	231

At the composting site the first year nitrogen accumulation was considerably more than the measured loss from the compost piles. This may be an artifact of our sampling grid happening to overlay on high nutrient input regions, with extrapolation to surrounding soil that may not have received so much N. In year two the accumulation is about half the measured losses, with the cumulative accumulation still somewhat greater than the cumulative loss. We suspect this result is still skewed by site heterogeneity, and look forward to analyzing the results from soil sampling in subsequent years. Nonetheless, this is strong evidence that significant N leaching can occur at an unlined outdoor manure composting site, especially in humid climates with moderate to high precipitation.

Discussion

Although deep-bedded systems appear to meet many of the criteria of a sustainable manure management system (Burton 1997, Richard and Choi 1999), losses of nitrogen during within the hoop structure and during subsequent composting are of potential environmental concern. Soil sampling results indicate that very little of the loss within the hoop structure can be accounted for in the shallow soil profile, so the remaining losses are either leaching deep into the groundwater or being emitted into the air. Although elevated N concentrations in the 70 cm depth are evidence that leaching cannot be entirely ruled out, deep percolation is unlikely to be a major route of loss within the structure, since the entire bedded pack is under a roof and dry bedding is normally added whenever the dunging area gets saturated. Outside at the unroofed composting site leaching appears much more significant, with an accumulation of N in the soil profile during in the first year almost triple the documented N losses, and an additional second year accumulation equal to about half the second year N losses.

Nitrate and ammonia runoff and leaching have previously been observed at outdoor composting sites, particularly those with low C:N ratios such as occurred in this study (Rymshaw et al., 1992). Runoff from composting sites can be managed with several low cost treatment techniques (Rynk and Richard, 2000), but excess leaching of nutrients can only be mitigated by reducing surface infiltration or moving the composting site. Moving sites on an annual basis may be a realistic option for some agricultural composting facilities with large available acreages, and crops could be grown to extract accumulated nutrients from the site. But most composting sites are likely to be fixed in place, so understanding and mitigating any groundwater quality impacts will be an important part of improving compost facility design.

Several studies of other bedded livestock systems have indicated a significant N losses through gas emissions, including NH_3 and N_2O (Andersson, 1996; Dewes, 1996; Groenestein and Van Faassen, 1996; Asteraki et al., 1997). Nitrous oxide is an indicator of anoxic or anaerobic regions within the bedded pack, and implies a potential for significant emissions of N_2, the most reduced product of denitrification. Tam (1995) documented high numbers of both nitrifying and denitrifying bacteria in a deep litter system. NH_3 and N_2O emissions have also been reported during composting of bedded manure (Martins and Dewes, 1992; Dewes, 1998;1999; Sommer and Dahl, 1999; Tiquia and Tam, 2000) and other organic residues (Hellmann et al., 1997; He et al., 2000).

The environmental impact of these emissions are significant, with NH_3 a major factor in soil acidification (Groot Koerkamp, 1994) and CH_4 and N_2O being potent greenhouse gases, with their global warming impact estimated respectively at 21 and 290 times that of CO_2 on a mass basis (NRC,1992). Dinitrogen, N_2, is in contrast a harmless and largely inert gas, comprising about 80% of the earth's atmosphere. Thus emission of N_2 is generally considered environmentally benign, although like other N losses it represents a net loss of nitrogen from the agroecosystem, and this loss is likely to be compensated for by fossil fuel intensive synthetic N fertilizers (Richard and Choi, 1999). Optimal design and management of deep-bedded and composting systems should therefore strive to reduce overall N losses, and bias those losses which must occur to N_2 rather than N_2O or NH_3.

Conclusion

The mass balance analysis of deep bedded hoop structures identified significant N losses from the bedded pack (54 ± 6% of the excreted manure; 3.9 kg/pig) but negligible P losses in the hoop. Both N and P losses at the compost site were significant (19 ± 10% and 21 ± 21% of the excreted manure respectively). After losses in both the hoop and the composting process, the nutrient quantities remaining were 1.9 ± 0.4 kg N/pig and 1.0 ± 0.3 kg P/pig.

10% or less of the N losses from the hoop accumulated in the top 1.2 m of soil, and that net accumulation was entirely in the first year. Most N losses within the hoop structure appear to be in gaseous forms, e.g. N_2, N_2O, and NH_3. Two of these gases, nitrous oxide and ammonia, can affect air quality both within the hoop and beyond. Improved management of these gaseous losses in bedded livestock systems will be important to making these systems environmentally sustainable.

Although soil sample variability precluded a direct correlation between nitrogen losses and soil accumulation at the composting site, high apparent soil accumulations did indicate that a considerable fraction of the N losses observed at the composting site are being leaching into the soil. Design and management strategies to mitigate this leaching loss are likely to be necessary for manure composting facilities in humid regions located near vulnerable groundwater resources.

The mass balance results quantified some of the major losses of nutrient from bedded swine production in naturally ventilated hoop structures. More detailed investigations of the nature of these losses, as well as similar evaluations of other livestock housing and manure management systems will facilitate a better understanding of nutrient flows and losses, and ultimately more environmentally sound system management and design.

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