Novel Manure Management Technologies in No-Till and Forage Systems: Introduction to the Special Series

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Surface application of manures leaves nitrogen (N) and phosphorus (P) susceptible to being lost in runoff, and N can also be lost to the atmosphere through ammonia (NH₃) volatilization. Tillage immediately after surface application of manure moves manure nutrients under the soil surface, where they are less vulnerable to runoff and volatilization loss. Tillage, however, destroys soil structure, can lead to soil erosion, and is incompatible with forage and no-till systems. A variety of technologies are now available to place manure nutrients under the soil surface, but these are not widely used as surface broadcasting is cheap and long established as the standard method for land application of manure. This collection of papers includes agronomic, environmental, and economic assessments of subsurface manure application technologies, many of which clearly show benefits when compared with surface broadcasting. However, there remain significant gaps in our current knowledge, some related to the site-specific nature of technological performance, others related to the nascent and incomplete nature of the assessment process. Thus, while we know that we can improve land application of manure and the sustainability of farming systems with alternatives to surface broadcasting, many questions remain concerning which technologies work best for particular soils, manure types, and farming and cropping systems.

A p p l i c a t i o n  o f  m a n u r e  t o  s o i l s  u n d e r  n o - t i l l  a n d  p e r e n n i a l  f o r a g e  m a n a g e m e n t  p o s e s  e n v i r o n m e n t a l  a n d  a g r o n o m i c  t r a d e - o f f s.  W h i l e  t h e  a b s e n c e  o f  t i l l a g e  a n d  m a i n t e n a n c e  o f  a  p e r e n n i a l  c o v e r  p r o m o t e  s o i l  q u a l i t y  a n d  m i n i m i z e  e r o s i o n,  t h e  c o n v e n t i o n a l  p r a c t i c e  o f  s u r f a c e  a p p l i c a t i o n  o f  m a n u r e  t o  n o - t i l l  a n d  f o r a g e  s o i l s  l e a v e s  t h e  m a n u r e  v u l n e r a b l e  t o  p r o c e s s e s  t h a t  m a y  a d v e r s e l y  i m p a c t  t h e  e n v i r o n m e n t.  N u t r i e n t  l o s e s  f r o m  s u r f a c e  a p p l i c a t i o n  o f  m a n u r e  c a n  d e g r a d e  s u r f a c e  w a t e r  q u a l i t y,  w h i l e  e m i s s i o n s  o f  N H₃  r e p r e s e n t  a n  e c o n o m i c  l o s e  o f  N  t o  f a r m e r s  a n d  p o s e  a  r i s k  t o  s u r f a c e  w a t e r  q u a l i t y  w h e n  t h e  N H₃  i s  r e d e p o s i t e d.  T h e  C h e s a p e a k e  B a y  M o d e l,  f o r  e x a m p l e ,  e s t i m a t e s  t h a t  1 8 %  o f  N  a n d  2 7 %  o f  P  e n t e r i n g  t h e  C h e s a p e a k e  B a y  c o m e  f r o m  m a n u r e  a p p l i c a t i o n  t o  a g r i c o u r l a n d s  ( C h e s a p e a k e  B a y  P r o g r a m,  2 0 1 0).  V e r b r e e  e t  a l.  ( 2 0 1 0 )  c o m p a r e d  n u t r i e n t  l o s e s  i n  r u n o f f  f o l l o w i n g  s u r f a c e  a p p l i c a t i o n  o f  m a n u r e  t o  n o - t i l l  s o i l s  w i t h  l o s e s  f r o m  s u r f a c e  a p p l i e d  m a n u r e  t h a t  w a s  s u b s e q u e n t l y  i n c o r p o r a t e d  i n t o  t h e  s o i l  b y  t i l l a g e.  T h e  n o - t i l l  d e c r e a s e d  s e d i m e n t  l o s e  c o m p a r e d  w i t h  t h e  t i l l e d  t r e a t m e n t,  b u t  t h e  s o l u b l e  N a n d  P  l o s e s  w e r e  g r e a t e r  f r o m  t h e  n o - t i l l  o n  p o o r l y  d r a i n e d  s o i l s  d u e  t o  r u n o f f  w a t e r  i n t e r a c t i n g  w i t h  m a n u r e  o n  t h e  s o i l  s u r f a c e.

A substantial number of best management practices (BMPs) associated with manure applications, ranging from riparian buffers to diet modification aimed at decreasing nutrient concentrations in manure (Maguire et al., 2007), are designed to lower nutrient losses to surface waters. One BMP that has not been heavily studied, and has not been widely adopted, is manure placement below the soil surface in no-till and forage systems. In an overview of the findings from the Fifth International Phosphorus Workshop, Kronvang et al. (2009) reported that future research should be focused on filling the knowledge gap of novel manure management, including manure injection. There is hope that improved manure management, such as manure injection, can improve N capture through limiting NH₃ volatilization as well as decreasing negative impacts of N and P loss on surface waters.

Surface application of manure is currently favored by most farmers because it is fast and relatively cheap, whereas technologies such as manure injection require more expensive equipment and are typically slower (Maguire, 2008). However, improved N use efficiency by crops will help to compensate for some of these constraints since manure injection almost eliminates NH₃ volatilization losses (Sommer and Hutchings, 2001), substantially increasing


**Abbreviations:** BMP, best management practice; DPR, dissolved reactive phosphorus.


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manure injection, an array of new technologies have emerged that improve the incorporation or infiltration of manure into soil, while minimizing disturbance and preserving surface residue cover. Bittman et al. (2005), for example, reported that banding dairy manure behind an aerator decreased NH$_3$ volatilization by 47% relative to surface broadcasting.

This special collection of papers presents the latest research being conducted on improving manure management in no-till and forage systems where incorporation of manure by tillage is not possible. It compares a broad range of improved technologies for manure management relative to traditional surface broadcasting. The collection includes many aspects of these technologies, such as impact on crop yields, odors, economics, NH$_3$ volatilization, and nutrient and sediment losses in runoff.

**Implements Available and Manure Placement**

Other than surface broadcasting, a wide range of alternatives is now available to improve manure management in no-till and forage systems. These alternative manure application technologies can be categorized on the basis of the manures that they can handle (liquid or dry) and their mode of action, which affects how manure is placed on or into a soil (Fig. 1):

1. The “sleigh foot” or “traveling shoe” is designed for liquid manure applications to standing forages such as fescue (*Festuca arundinacea* Schreb L.), as it applies the manure in bands on the soil surface without covering the leaves (Fig. 1a). Without the sleigh foot, the timing of surface broadcasting of manure is limited to before the forage is growing or immediately after harvest (Bittman et al., 1999). By broadening the window for manure applications, manure can be applied several times during the growing season to more closely match forage N requirements and save farmers money by reducing the required size of manure storage systems. The sleigh foot can also increase N recovery by decreasing NH$_3$ volatilization due to decreased manure surface area and protection from wind since manure is placed below the forage canopy (Bittman et al., 1999; Maguire et al., 2011).

2. Disk or chisel injectors create a slit in the soil and a drop tube places the manure in the slit (Fig. 1b). Sometimes there are closing disks to ensure that the slit is closed after the manure is injected, especially for disk injectors. It is essential that the slit is closed; otherwise NH$_3$ losses to the atmosphere can continue. The deeper the slits, the greater the rate of manure that can be applied, but deeper injection may increase the risk of N leaching losses (Maguire et al., 2011). Few studies have detailed this, but injection is often limited to approximately 15 cm, which can provide sufficient manure nutrients for most crops without risking excessive N leaching (Ball Coelho et al., 2007).

3. Aerators, including core and solid tine, can be used to improve the incorporation of liquid or dry manures. Aerators punch holes in the ground and can be used either in direct conjunction with manure application or as a separate treatment before or after manure is applied. When liquid manure is applied in conjunction with aeration, manure can be surface broadcast or placed in bands over the aeration holes to increase the proportion entering the holes and decrease surface area of manure (Fig. 1c). Aerators can also be converted to perform mild tillage, replacing less-aggressive tillage operations such as disking. Aerators require less draft energy than disk or chisel injectors, but manure is not scaled under the soil surface, meaning that reductions in NH$_3$ volatilization are not as great (Sommer and Hutchings, 2001). Aerators can also increase infiltration of rainfall and decrease nutrient losses in runoff, but results have not been consistent (Franklin et al., 2007).

4. Chisel injectors can have many minor variations between specific models and manufacturers, but one significant development is the sweep that can be placed on the bottom (Fig. 1d). The aim of this sweep is to promote horizontal mixing of manure with the soil and horizontal tillage that disrupts macropores and thus decrease N leaching losses. The horizontal mixing of the manure with the soil can be seen by comparing Fig. 1b for the chisel with no sweep to Fig. 1d with the sweep.

5. A recent technological advance is the development of the subsurface applicator for poultry litter, which is the first subsurface applicator available for solid manures (Fig. 1e). Poultry litter does not flow like liquid manure due to its inconsistent texture and relatively low moisture, making it extremely difficult to inject. However, a subsurface litter applicator has been developed that grinds the litter with augers as it moves the litter over chutes through which it falls by gravity into furrows within the soil (Pote et al., 2009, 2011). As poultry litter is much drier than dairy and other liquid manures, the volume applied is much less, so that the subsurface litter applicator only needs to cut a slit about 5 cm deep into which the litter is applied before the slit is closed (Fig. 1e).

For examples of these implementations, see the photographs of a disk injector, a chisel injector with sweeps, and an aerator set up with banding of manure, in the review by Maguire et al. (2011).

**Novel Manure Management Collection of Papers**

A review of existing literature is presented by Maguire et al. (2011), and it serves as a detailed introduction to this collection. This review covers the various alternatives to surface application of manure and the measured effects on environmental and agronomic factors. Specifically, Maguire et al. (2011) cover the effects of the alternatives to surface application of manure on surface residue, manure distribution, water quality impacts through nutrient losses in runoff and leaching, effects on air quality through NH$_3$ volatilization, greenhouse gases and odor, and root growth and crop yield. Maguire et al. (2011) also identify knowledge gaps and research needs, which will add to the existing literature and address important long-term issues. Some of these are detailed issues, such as the impact of manure injection on the N and C cycles, and the interactions of “N, P and sediment losses in runoff, N leaching, NH$_3$ volatilization, odor, and yield.” However, if farmers are going to move away from surface application of manure, the most important need is the economic assessment of the various alternative technologies that are available.
Placement of manure, either under the soil surface in injection slits or in aeration pockets, will have a major impact on the effectiveness of each manure application method. Wu and Chen (2011) developed a two-dimensional model to evaluate how manure moves when placed in an aeration pocket created by a rolling tine. The lateral spread of manure did not vary with injection depth, while the vertical thickness and cross-sectional area did increase with injection depth. The model predicted that aeration pockets with a larger area promoted better mixing of the manure with soils and reduced N losses. However, field validation showed that the model was better at predicting lateral spread and vertical thickness of the manure than it was at predicting the cross-sectional area.

Water Quality

Aerating soils can have a variable effect on nutrient losses in runoff (Maguire et al., 2011). Franklin et al. (2011) found that slit aeration could increase infiltration, decrease runoff, and thus reduce soluble P losses by 35% in fields with well-drained soils, but not in poorly drained soils. In plot-scale studies, when pasture was fertilized with broiler litter, core aeration reduced loads of total P and dissolved reactive P (DRP) in runoff (Franklin et al., 2011). de Koff et al. (2011) used an Aerway aerator (SAF Holland, Holland, MI) on pasture to evaluate its effectiveness at decreasing nutrient losses in runoff, when poultry litter or swine manure were applied after aeration, and their results were inconclusive. Under rainfall simulation on small plots, aeration decreased nutrient loads in runoff from two out of three soils. In larger plots (0.23 ha), aeration decreased P loads in the first 3 mo but increased P load and runoff volume over the entire year, compared with a nonaerated plot (de Koff et al., 2011). In the field-scale studies, Kovar et al. (2011) injected manure either with a disk or chisel injector and reported that the concentrations and loads of DRP and total P were not elevated above that of a no-manure treatment. This indicates the huge potential for manure injection to decrease negative environmental impacts associated with P losses in runoff following land application of manure. Using intact soil columns in a laboratory study, Glasner et al. (2011a,b) investigated the influence of injecting dairy slurry on leaching of manure components, relative to surface broadcasting. Slurry was amended with bromide, and injection of this slurry into a loam soil significantly enhanced diffusion of bromide into small pores compared with surface application (Glasner et al., 2011a). As leaching occurs predominantly through larger pores, injection decreased the amount of bromide leached compared to surface application. However, no effect of injection on leaching of bromide was observed for a loamy sand and a sandy loam soil (Glasner et al., 2011a). In the same set of experiments, injection of dairy slurry decreased P leaching in the loam and sandy loam, but not significantly in the loamy sand (Glasner et al., 2011b). They attribute lower P leaching losses with injection to placement away from major flow pathways in the finer textured soils, as well as greater retention of inorganic P due to more contact of slurry with adsorption sites (Glasner et al., 2011b).

Nitrogen Recovery and Crop Yields

Increased N recovery from manures when they are applied by improved technologies, relative to surface broadcasting, is generally attributed to decreased NH₃ volatilization (Dell et al., 2011). This increased N recovery often translates into increased crop yields for improved technologies compared with surface broadcast of manure. Lalor et al. (2011) show that using a traveling shoe (Fig. 1a) in forage decreased NH₃ volatilization, and increased N recovery and thus forage yield, relative to surface broadcasting dairy slurry. Pfiske et al. (2011) also used a traveling shoe to apply dairy manure in bands to forage. The traveling shoe decreased NH₃ losses by an average of 52 and 29% for high (50 m⁻³ ha⁻¹) and low (25 m⁻³ ha⁻¹) manure rates, respectively. Most of these NH₃ losses occurred in the first 24 h following the manure application, whether the manure was surface broadcast or applied using the traveling shoe (Pfiske et al., 2011). As NH₃ losses are dependent on weather variables such as temperature and wind speed, this result indicates the importance of weather conditions in the first day after manure application.

Although manure injection can almost eliminate NH₃ volatilization, increased denitrification could offset as much as half
of the N conserved in some cases (Dell et al., 2011). One of the products of denitrification is the greenhouse gas nitrous oxide, but due to limited studies this requires more investigation. At present, the economic and environmental benefits of decreasing NH3 volatilization through manure injection are thought to outweigh any concerns over denitrification (Dell et al., 2011). Powell et al. (2011) measured N losses through NH3 volatilization and leaching from surface-applied and injected manure treatments over a 4-yr period. They report that of the N applied, N losses through these pathways totaled 21.7% for surface broadcasting, compared with only 9.1% from injected manure due to decreased NH3 volatilization. Although injecting manure decreased N losses compared with surface application, this did not translate into significant increases in crop N uptake or yield (Powell et al., 2011). Kovar et al. (2011) compared the merits of injecting manure into a cover crop with either a disk injector or a chisel injector. They found that the chisel injector did substantial damage to the cover crop while the disk injector did not, resulting in the cover crop having improved yield; in addition, P uptake in spring was three-fold greater for the disk injector compared with the chisel.

de Koff et al. (2011) found aerating had no consistent effect on yield when pastures were aerated before surface broadcasting of poultry litter or swine manure. This agrees with highly variable yield results for aeriation in previous literature (Maguire et al., 2011). Bittman et al. (2011) separated solids from dairy manure and evaluated crop performance after surface banding the remaining liquid, which they called the separated liquid fraction. Banding of this liquid fraction produced greater forage yields than banding equivalent mineral N rates of whole dairy manure, which they attributed to the rapid infiltration of the liquid fraction decreasing the potential for NH3 volatilization (Bittman et al., 2011). They suggest that using the separated liquid fraction close to barns, while transporting the lighter solids fraction further, would be economically beneficial as farmers would not be paying to transport water.

New Systems to Inject Dry Poultry Litter

Systems to inject liquid manure have been available for several years, but directly placing dry materials below the soil surface represents a much greater challenge as dry materials cannot be pumped under pressure into the soil. Three papers, by Watts et al. (2011), Kibet et al. (2011), and Pote et al. (2011), provide possible new solutions to overcome the technical challenges of achieving subsurface application of dry poultry litter. Pote et al. (2011) review the evolution of the poultry litter injector for dry manures. Injecting poultry litter with this machine successfully decreased NH3 volatilization and nutrient losses in runoff by more than 90% compared with surface broadcasting poultry litter (Pote et al., 2011). This means that nutrient losses in runoff from injected litter were statistically indistinguishable from those of the unfertilized (control) plots. The injection of poultry litter also increased nutrient use efficiency and yields relative to surface broadcasting of poultry litter, probably due to the lower NH3 emissions and crop use of this captured N (Pote et al., 2011). Kibet et al. (2011) used the same litter injector as Pote et al. (2011) and showed that litter injection decreased total P loss in surface runoff (1.9 kg ha−1) compared with surface broadcasting (4.8 kg ha−1) in the first runoff event. However, there was no significant difference between total P losses in runoff from injected versus surface broadcast poultry litter for the second runoff event (Kibet et al., 2011). Watts et al. (2011) used a four-row prototype subsurface applicator developed at the USDA–ARS National Soil Dynamics Laboratory to place poultry litter into subsurface bands in established bermudagrass (Cynodon dactylon L.) pasture. Compared with surface broadcasting of poultry litter, subsurface application of litter decreased concentrations of inorganic N 91%, total N 90%, DRP 86%, and total P 86% in runoff water. The results of subsurface application of the poultry litter were so dramatic that the clarity of runoff water from the injected litter was substantially superior to that from surface broadcast poultry litter (Watts et al., 2011).

Odor

The impact of manure applications often focuses on nutrient use efficiency and implications for nutrient losses and water quality. However, odor issues can also be a huge problem for land application of animal manures, especially where people live close to agricultural fields receiving manure (Mukhtar et al., 2004). Brandt et al. (2011) evaluated manure application methods for their effects on odor. They report that odor decreased significantly in the order surface broadcast > aeration infiltration > surface + chisel incorporation > direct ground injection = shallow disk injection > no manure control. Odor reduction benefits generally persisted for at least 24 h. This shows not only that the manure application method has a profound influence on N recovery and water quality but that it can also greatly affect nuisance odors.

Economics

The main reasons that surface broadcasting of manures is the method of choice for farmers is that it is the fastest and cheapest method for land applying manure. The speed of manure application is especially important for manure application to spring-planted row crops, where farmers have a relatively small window to apply manure and plant crops. Injection equipment is also more expensive to buy and maintain, and uses more energy, than surface broadcasting. However, the increased costs associated with improved manure management can be at least partially offset by increased NH3–N capture and thus improved yield, as discussed above. Rotz et al. (2011) used a process level farm simulation model to evaluate the economic viability of changing away from surface broadcasting of liquid dairy and swine manure. Simulations over 25 yr of weather on three Pennsylvania farms indicated that shallow disk injection increased profit by US$340 yr−1 on swine and cow–calf beef operations under grass production. This manure injection method also improved air and water quality by reducing NH3 volatilization and nutrient losses in runoff. However, for grass-based grazing on dairy farms, or on a dairy farm where manure nutrients were available in excess of crop needs, shallow disk injection reduced NH3 volatilization and nutrient losses in runoff but had either little impact on farm profit or slightly decreased profitability (Rotz et al., 2011).

Future Research Needs in Manure Management Technologies

In their review of the literature, Maguire et al. (2011) specify six knowledge gaps, which can be summarized as follows: (i) develop a standard research protocol, so that studies can be easily

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compared; (ii) measure multiple variables in future studies; (iii) include impact of manure management on emerging contaminants, such as hormones and pathogens; (iv) obtain more information concerning long-term impacts on N and C cycles; (v) perform a comprehensive economic assessment, as this is vital to adoption; and (vi) study other details such as ideal depths for manure injection and the need for starter fertilizers. In addition to these needs, we must remember that manure and farming are diverse and that one size will not fit all. A large dairy farm that owns its own equipment will deal differently with management issues and economics than will a small dairy farm, which relies on custom applicators for manure spreading. A poultry farm, which relies on imported feed, will also have different priorities than a dairy, which relies on manure to produce crops for animal feed. Therefore, much more scientific and economic assessment remains to be performed in this developing field.

Conclusions

This special collection includes two reviews of existing literature dealing with the breadth of technologies now available and their environmental and agronomic impacts, and the N balance, as well as 15 new studies on alternatives to surface broadcasting of manure. As we move toward sustainable manure management that deals constructively with animal manures to maximize nutrient use efficiency and minimize negative effects on air and water quality, improvements over surface broadcasting are necessary. This collection covers a broad array of technologies and their impacts, but much more work remains before we have comprehensive answers to which technologies are most appropriate and cost effective in field- and farm-specific situations.

References


