Manure Application Technology in Reduced Tillage and Forage Systems: A Review

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Managing manure in reduced tillage and forage systems presents challenges, as incorporation by tillage is not compatible. Surface-applied manure that is not quickly incorporated into soil provides inefficient delivery of manure nutrients to crops due to environmental losses through ammonia (NH_3) volatilization and nutrient losses in runoff, and serves as a major source of nuisance odors. An array of technologies now exist to facilitate the incorporation of liquid manures into soil with restricted or minor soil disturbance, some of which are new: shallow disk injection; chisel injection; aeration infiltration; pressure injection. Surface banding of manure in forages decreases NH_3 emissions relative to surface broadcasting, as the canopy can decrease wind speed over the manure, but greater reductions can be achieved with manure injection. Soil aeration is intended to hasten manure infiltration, but its benefits are not consistent and may be related to factors such as soil drainage characteristics. Work remains to be done on refining its method of use and timing relative to manure application, which may improve its effectiveness. Placing manure under the soil surface by injection offers much promise to improve N use efficiency through less NH_3 volatilization, reduced odors and decreased nutrient losses in runoff, relative to surface application. We identified significant gaps in our knowledge as many of these technologies are relatively new, and this should help target future research efforts including environmental, agronomic, and economic assessments.

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Row crops under reduced tillage and forages account for a large proportion of agricultural land in North America. In recent years, reduced tillage in its various forms, from no-till to strip-till, has rapidly expanded with lower energy costs and time demanded by tillage operations being key reasons for farmer adoption (Lal et al., 1990). Minimizing tillage has been shown to increase organic matter in surface soil relative to routine tillage (Wander et al., 1998), as well as to improve soil moisture retention (Blevins et al., 1971) and even conserve soil N (Spargo et al., 2008). Greater stability of soil structure and more complete residue cover with reduced tillage can lower sediment and related nutrient losses in runoff compared with conventional tillage (Harrold and Edwards, 1974; Garcia et al., 2008).

Application of manure to forage soils and those under reduced tillage represents an area of continued concern, as manure is typically surface applied and not followed by tillage incorporation. Surface application of manure can exacerbate ammonia and odor emissions as well as loss of dissolved nutrients in surface runoff (Keeney, 1982; Kleinman et al., 2002). In addition, repeated surface application of manure to no-till soils may result in severe stratification of soil chemical properties, requiring periodic tillage to mix the soil (Sharpley, 2003). However, tillage is incompatible with forage maintenance and can reverse the soil quality and environmental benefits of reduced tillage (Pierce et al., 1994). Thus, the challenge is to find methods of manure incorporation that reduce environmental impacts but leave crop residue and forage on the surface to protect soil from erosion.

Recent technological advances have made manure incorporation in row crops under reduced tillage and forage systems possible. These technologies hold great potential for decreasing the negative effects of surface application of manure without incorporation by tillage. A growing number of recent research articles describe the effect of individual technologies on soil, water, and atmospheric variables. This review provides an overview of technologies for reduced-tillage and forage systems, summarizes their

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performance with respect to soil and environmental variables, and identifies gaps in this relatively new area of knowledge.

Types of Manure Application Technologies

Technologies to incorporate liquid manure into soils with minimum disturbance can be placed into several broad categories (Meisinger and Jokela, 2000). *Disk injectors* typically employ coulters to cut residue and create a furrow in the soil, a drop hose or supply tube to place manure in the furrow, and a closing implement to seal the soil surface after manure has been injected (e.g., parabolic disks, pressing wheel). Figure 1a shows an example of a disk injector with closing disks to close the slit after manure is injected. Because disk injection is often limited to the upper 10 to 15 cm of soil it is frequently termed "shallow disk injection." *Chisel injectors* cause slightly more soil disturbance than disk injectors, typically dragging a C-type shank through the soil and injecting manure behind it through a drop hose. Chisel injectors cover a range of injection depths and may be fitted with a narrow spike to minimize the zone of soil disturbance or a winged sweep to extend the horizontal distribution of the injected manure (Meisinger and Jokela, 2000; Fig. 1b). *Aerators* include core (and hollow) and solid-tine configurations and can be used to increase infiltration of liquid manure by punching holes, or pits, into the soil before manure is surface broadcast or banded over the holes, or aerators can partially incorporate previously applied manure by running them at an angle as discussed later (Franklin et al., 2006; Fig. 1c). Core aerators create holes by removing a small soil core, while solid-tine aerators punch a hole with a solid tine. Solid-tine aerators are most commonly used in agricultural settings and have the ability to lightly cultivate the surface soil after manure application by changing their angle of entry and the severity of soil disturbance (Franklin et al., 2007). *High-pressure injectors* were developed in Scandinavia for stony, steep pasture and sod soils where other forms of injection were not feasible (Morken and Sakshaug, 1998). These systems employ a specialized pump to force pressurize slurry into the ground in elongated, discontinuous cavities without the use of a cutting implement. *Surface banding* of manure leads to bands of manure on the soil surface rather than complete soil coverage with manure. Banding can be done with several implements such as drag hoses that apply manure directly on the surface or from 20 cm or so above the soil surface, or by drag-shoes (also called trailing foot, sliding shoe, or sleigh foot) that can penetrate crop cover and place the manure in bands directly on the soil surface without damaging the crop (Bittman et al., 1999; Rodhe et al., 2006).

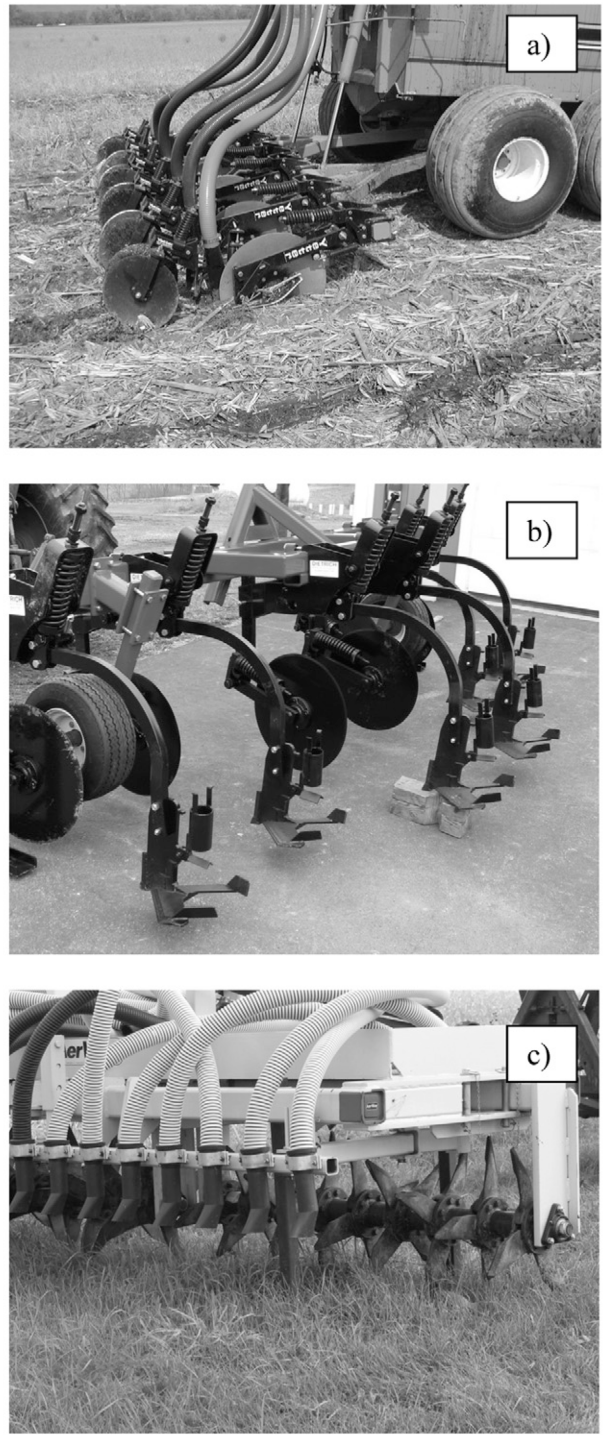

Fig. 1. Examples of novel manure application technologies currently available, including (a) a disk injector system that is capable of injecting liquid manure to a depth of 15 cm; (b) chisel injector with sweeps, which includes a disk to cut surface residue; and (c) an aerator set up to band liquid manure over the injection slots.

Effects of Manure Application Method

Soil Impacts and Manure Distribution

Methods of manure application differ greatly in their effect on soil surface conditions including residue, soil tillage disturbances, and manure distribution. Because most methods of directly incorporating manure into soil involve the creation of furrows or pits where manure can be placed, the impact of different applicators is often spatially discrete, or zonal, in nature. Therefore, while disturbances within the zone of manure application may be quite severe, when observed at a field scale these disturbances are often comparable to those caused by a no-till planter.

Residue and Soil Disturbance

Maintaining soil residue cover is a primary objective of reduced tillage systems and residue cover represents a readily measured indicator of the surface disturbance imposed by a manure application method. The extent of residue disturbance is influenced by the residue cutting and tillage actions of a manure applicator, spacing of implements, speed of travel, and the residue cover itself (Chen et al., 2001; Sexton et al., 2005; Shelton, 2006). While preservation of soil residue cover is clearly best with broadcasting manure, aerator applicators and shallow disk injectors can be quite discrete in their disturbance of residue, resulting in relatively minor removal of existing cover, and most new methods for incorporating manure without tillage are capable of conserving at least 30% of the existing cover when conditions are favorable (Table 1). The shallow disk injector leads to the highest levels of residue, consistently being >61%. It is notable that the performance of an applicator in preserving residue cover can vary greatly with different residues. In general, corn grain (*Zea mays* L.) residue cover has the potential to be well preserved because of its rigidity and sheer volume. In contrast, fragile residues such as soybean [*Glycine max* (L.) Merr.] and small grains tend to break down with even minor disturbance so are harder to maintain following manure application.

Soil disturbance by manure application methods arises from the tillage action of individual implements interacting with pressurized slurry as well as compaction by tractor and spreader tires (Chen et al., 2001; Rahman et al., 2005). In general, the largest disturbances are associated with chisel implements, particularly those fitted with sweeps, while disk and aerator systems can be managed to have low to negligible impacts, particularly at the soil surface. In a trial of five application systems representing three categories of application method (chisel, shallow disk, and aerator), Sexton et al. (2005) observed more than a threefold difference in the percentage of surface soil disturbance, with the greatest associated with chisel injection (spike and sweep), followed by shallow disk and aerator. They noted substantial differences in soil disturbance among shallow disk injection implements, with a large, offset-opening coulter system producing up to 43% less disturbance than a straight coulter system at low speed. In that study, disturbance increased an average of 30% when speed increased from 2.6 to 10.6 km h^{-1}. Elsewhere, Rahman and Chen (2001) documented average differences in soil surface disturbance widths of roughly 600 mm for two different chisel injectors with sweeps, 200 mm for a tandem parabolic disk injector, and 150 mm for a shallow disk injector.

Manure Exposure

Although relatively little has been published on the phenomenon of manure splash or exposure on the soil surface, it represents a principal measure of performance of manure injection equipment and has environmental implications for all liquid manure application methods (Rahman et al., 2005). Exposure of applied manure on the soil surface largely controls the availability of manure constituents to runoff and atmospheric transport processes (Chen and Tessier, 2001; Kleinman et al., 2002). Maximum exposure of manure occurs with surface application, and can be decreased but not eliminated by surface banding methods, as with banding of manure behind aeration pits (Bittman et al., 2005; Harrigan et al., 2006). With injectors, surface exposure of manure occurs when furrows are not sealed with a closing implement or when injection equipment is forced above the soil surface, such as by stones, uneven topography, and high speed. Rhaman et al. (2005) concluded that larger sweeps and lower ground speeds minimized manure exposure with chisel injection. Exposure of injected manure also occurs when pressurized slurry exceeds the storage capacity of the furrow (e.g., excessive application rate relative to antecedent soil moisture), deflections occurs off an impervious surface (e.g., stone), or soil-closing apparatus is inadequate (Rahman and Chen, 2001; Rahman et al., 2005; Sexton et al., 2005).

Table 1. Percentage of initial residue cover that remains after manure has been applied. Results summarized from Hanna et al. (2000), Daverede et al. (2004), Sexton et al. (2005), Harrigan et al. (2006), and Shelton (2006).

Method	Surface residue remaining		
	Corn	Soybean	Small grain
	%		
Broadcast	99	96	–
Chisel injection			
Chisel with sweep	30–65	5–77	46–62
Spike/knife	76–78	56–64	35–47
Disk injection			
Shallow disk	80–95	61–80	83–89
Tandem disk	35–76	5–25	–
Aerator	–	–	64–90
Tillage			
By disk	63	30	–

Water Quality

Residue and soil disturbances caused by manure application as well as manure exposure can interact to significantly impact surface runoff processes. Hampering interpretation of the available literature is the prevalence of studies that only evaluate manure application methods in the near term, introducing bias toward certain conditions and processes that may not transfer to longer term generalizations (Garcia et al., 2008). For instance, Little et al. (2005) measured runoff volume under simulated rainfall from surface-applied manure with no incorporation, or incorporated with an array of tillage methods. Their results showed that increasing cultivation lowered surface runoff volume by increasing simulated rainfall infiltration. However, results could not be generalized as this study included only one rainfall simulation after tillage, and did not test the effects of crusting and surface sealing that would be expected to become more apparent with subsequent rainfall events (Panuska et al., 2008). Prudent assessment of manure application method effects on surface runoff must consider the limits imposed by experimental designs.

Surface Runoff Volume

The effects of manure applicators on runoff volumes are varied, and are as dependent on site conditions as the applicators themselves (Table 2). In poorly drained soils where seasonal moisture saturation from rising water tables tends to control surface runoff (i.e., "saturation excess" runoff; Nash et al., 2002), manure applicators and tillage can be expected to have negligible effects on runoff processes. In better drained soils where infiltration excess runoff predominates, some manure applicators may improve rainfall infiltration, but the effects are primarily witnessed in the near term. For instance, one would expect to see the greatest reduction in surface runoff with aerator units, which are used to renovate compacted soils by increasing surface soil porosity, therefore moisture storage capacity, as well as by providing

Table 2. Changes in runoff properties caused by manure application methods relative to broadcast application (Burcham et al., 2008; Daverede et al., 2004; K.N. Johnson, P.J.A. Kleinman, D.B. Beegle, and H.A. Elliott, personal communication, 2009).

Method	Runoff volume		Erosion		Total P load		Dissolved P load	
	Row crop	Forage	Row crop	Forage	Row crop	Forage	Row crop	Forage
	—— L ha^{-1} ——		—— Mg ha^{-1} ——		———— kg ha^{-1} ————			
Chisel injection								
Spike/knife	–	–	–	–	94% less	–	–	–
Disk injection								
Shallow disk	–	3–35% less	0%	68% less	0–91% less	84% less	71–94% less	–
Aerator		0–81% less		28% more to 69% less	94% less	0–88% less	96% less	13–90% less
Tillage								
By moldboard plow	9–56% less	–	–	–	90% less	–	84% less	–
By chisel plow	14–66% less	–	0–97% more	–	90% more to 81% less		0–68% less	
By double disk	20% less	–	–	–	–	–	–	–

preferential flow pathways for infiltrating water from rain and manure. Indeed, van Vliet et al. (2006) observed that runoff volumes from aerated orchardgrass (*Dactylis glomerata* L.) receiving broadcast or banded liquid dairy and swine manures were 47 to 81% lower than from soils that were not aerated. However, Franklin et al. (2007) found that while aerating a well-drained tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbysh.] and bermudagrass (*Cynodon dactylon* L.) soil receiving broadcast poultry litter significantly lowered surface runoff volumes, aerating poorly drained soils did not. Elsewhere, Shah et al. (2004) observed that one of two aeration treatments on well-drained soils receiving manure lowered runoff volumes relative to other manure application methods, but the effect was observed in only one of six rainfall events.

Erosion

Relatively limited empirical data exist on erosion derived from modern manure application methods, but measurements of soil and residue disturbance and findings from tillage-related studies do provide insight into this area. It is reasonable to assume that manure application methods with the greatest disturbance of surface residue (Table 1) and soil physical properties, such as double disk openers and chisel injectors with broad sweeps, are most apt to increase erosion. Aerators and disk injectors have shown the potential to minimize erosion following manure application, although their performance can vary considerably depending on design and site conditions (Table 2). In the case of aerators, Butler et al. (2008) measured 28% *more* sediment in runoff from uncompacted, grassed soils undergoing core aeration than from soils without aeration. However, under compacted conditions, the core-aerated soils yielded 47% *less* sediment in runoff than did the unaerated soils. In that study, solid-tine aeration of compacted soils actually lowered sediment losses by 68% relative to unaerated conditions. Shah et al. (2004) measured significantly greater sediment concentrations from manured and aerated orchardgrass than those that received a surface manure application with no aeration.

Less has been reported on shallow disk injectors, but given the wide range in designs, it is likely that they too will range in performance. Sistani et al. (2009) tested a prototype method for incorporating poultry litter that employs a double disk opener and places ground litter in a shallow (<8 cm) trench. The lower erosion rates documented in their study likely reflect the contribution of vegetation and manure solids (i.e., "flocs" of light organic matter) to sediment in runoff, as has been documented by McDowell and Sharpley (2002), rather than differences in soil erosion.

Phosphorus

Because of the high concentration of P in most types of manure, surface-applied manure has a high potential to release P, particularly dissolved forms of P, to runoff water. K.N. Johnson, P.J.A. Kleinman, D.B. Beegle, and H.A. Elliott (personal communication, 2009) correlated dissolved P concentrations in runoff from six alternative manure application methods by the amount of water-extractable P that a particular method left on the soil surface ($r = 0.88$). Incorporation of manure into soil removes the potential for the direct transfer of manure P to runoff, but incorporation methods that simultaneously expose soil and disturb soil stability can exacerbate P losses over the long term due to eventual increases in erosion (Garcia et al., 2008; Panuska et al., 2008).

Tradeoffs in dissolved and particulate P losses are especially acute with methods of aggressive tillage and in soils that are highly erodible or have high concentrations of antecedent P. Allen and Mallarino (2008) evaluated P loss in runoff from broadcast swine manure in a corn–soybean rotation with and without incorporation by disk tillage 24 h, 15 d, and 6 mo after application. At 24 h, dissolved P and total P concentrations were greater from the unincorporated than the incorporated manure, consistent with other studies examining near-term trends in runoff after manure application (Kleinman and Sharpley, 2003; Little et al., 2005). After 15 d, however, differences in P concentrations had diminished substantially, and at 6 mo dissolved P losses were almost identical while particulate P losses were significantly elevated in the disk tillage treatment (Allen and Mallarino, 2008). Thus, the large reductions in runoff P losses following moldboard and chisel plowing reported in Table 2 are likely the product of studies that were not sufficiently long to document the temporal trends witnessed by Allen and Mallarino (2008).

Despite the prevalence of studies employing near-term assessment methods, there is widespread evidence that most forms of direct incorporation of manure that do not substantially increase erosion are effective in lowering P losses in runoff (Table 2). Again, results are highly site dependent, but there are a few studies to suggest that low disturbance methods of application decrease losses. Daverede et al. (2004) reported a 94% reduction in P runoff associated with chisel injection compared with broadcast manure application following soybean. Clear reductions in dissolved P loss have been reported with shallow disk injection relative to broadcast application. In one study, Burcham et al. (2008) observed a 71% decline in dissolved P loss with shallow disk injection relative to surface broadcast in no-till. Subsurface application of poultry manure, analogous to shallow disk injection of dry manure, has also been shown to decrease P in runoff relative to surface applications (Pote et al., 2003; Sistani et al., 2009).

Aerators can be used in various configurations to either facilitate infiltration of rain and manure water (aeration before application) or incorporate manure into the soil surface (aeration after application, with the aerator generally run at an angle to increase soil disturbance). Studies reported in Table 2 all reflect aeration before application, and therefore document the effects of aeration when manure remains on the soil surface. As a result, aeration benefits are primarily related to changes in infiltration and lowered runoff volumes, described above. For example, van Vliet et al. (2006) reported that aeration slots accounted for only 5% of the soil surface area, but their volume could contain more than half the volume of a fall dairy manure application. Franklin et al. (2007) found that aeration lowered P losses from a well-drained fescue–bermudagrass hay field but increased P losses from a poorly drained field receiving broadcast poultry litter. These findings are consistent with trends in runoff volumes and may also reflect spatial variability in natural runoff processes. Elsewhere, Butler et al. (2008) concluded that core aerators were more effective than solid-tine aerators and slit aerators in lowering P losses in runoff from tall fescue–bermudagrass. Other researchers have measured inconsistent or no effect of aerating manured orchardgrass vs. surface applying manure on dissolved P and total P losses in runoff (Shah et al., 2004).

Nitrogen

Surface runoff is not considered a dominant pathway for N transport, but can be of local significance. Several studies have shown that incorporating manure by tillage can decrease N losses in runoff initially, likely a function of minimizing the direct transfer of manure N to runoff water (Little et al., 2005; Panuska et al., 2008). Other methods that directly incorporate manure, such as injection, also have shown promise in controlling near-term transfers with results that are similar to those reported for P runoff. Pote et al. (2003) found that subsurface application of poultry litter to bermudagrass using a disk-type subsurface applicator lowered N loads in runoff from pasture soils by >80% compared with broadcast litter. Burcham et al. (2008) reported a 67% decrease in dissolved N runoff with shallow disk injection in no-till corn compared with broadcast manure, but did not observe any differences in total N losses in runoff.

Mixed results have been reported in the effect of aerator methods of manure application on N runoff, probably reflecting the surface placement of manure that remained as a direct source of dissolved nutrients in runoff. Shah et al. (2004) found no differences in nitrate losses in runoff following broadcast application of dairy manure after aeration of orchardgrass, and observed inconsistent trends in total N from six rainfall events. Franklin et al. (2006) also found that aeration had no significant effect on N losses in runoff from broadcast broiler litter applied to tall fescue and bermudagrass. However, van Vliet et al. (2006) observed 56 to 81% reduction in total N runoff from orchardgrass receiving dairy and swine manure broadcast or banded after mechanical aeration. They found that the first three runoff events after manure application accounted for more than a third of the annual N loads, attributing the reductions to improved infiltration of rainwater in those early events and lower runoff volumes.

Leaching

The literature quantifying manure application method effects on leaching losses of nutrients is relatively scarce, and is primarily oriented toward N leaching, which is strongly influenced by climate, soil properties, cropping system, and manure application rate (Ball-Coelho et al., 2007). Curt Dell (USDA-ARS, personal communication, 2010) found considerable variability in nitrate leaching between five manure application methods through well-drained soils under continuous corn. During 1.5 yr, Dell found roughly three times more nitrate leached from broadcast manure than from unamended soils. However, all forms of manure incorporation increased nitrate leaching relative to broadcast application: aerator, 34% more; chisel tillage, 30% more; shallow disk injection, 120% more. Elsewhere, Little et al. (2005) found greater concentrations of nitrate in subsurface water (60-cm depth) with manure that had been incorporated by moldboard plowing than with broadcast manure. This likely reflects the inversion caused by moldboard plowing with relatively little mixing of the inverted soil and the greater loss of NH_3 from surface broadcasting. Ball-Coelho et al. (2006) reported greater concentrations of N in tile drains under corn where manure had been injected rather than surface applied, at higher manure application rates to corn. However, this was not the case at lower rates of manure application that were close to crop requirements. Weslien et al. (1998) observed no differences in nitrate leaching losses from surface banded, harrow incorporated, and shallow injection methods of swine manure application to barley (*Hordeum vulgare* L.).

Air Quality

The role of manure as a source of atmospheric emissions of nutrients, odors, and greenhouse gases has been well established. In general, incorporation of manure into soil minimizes immediate transfers of volatile compounds to the atmosphere, but incorporation may exacerbate losses of some compounds following reduction in wet soils.

Ammonia Volatilization

Ammonia (NH_3) volatilization from manures applied to the soil surface typically results in a considerable loss of plant-available N, with losses commonly ranging from 30 to 70% of the total ammonium N (NH_4–N) content of the manures (Thompson and Meisinger, 2002). Manure incorporation with tillage can substantially reduce these losses, but the quantity of N conserved declines rapidly with time if tillage is delayed. For example, Bittman et al. (2005) reported that 85% of NH_3 volatilization occurred within 24 h for surface-broadcast and banded dairy manure applied to tall fescue. Injecting manure is an effective method of reducing NH_3 volatilization in most situations, allowing immediate incorporation even in systems where tillage is not possible (i.e., forage and no-till). Traditional manure injection technologies (e.g., knife, chisel and disk injectors) have been shown to reduce NH_3 emission by 40 to almost 100% compared with broadcast application (Hansen et al., 2003; Lambert and Bork, 2003; Misselbrook et al., 1996; Moseley et al., 1998; Smith et al., 2000; Wulf et al., 2002a) (Table 3). A 60% decline in NH_3 emission with the use of a high-pressure injection system was also observed (Morken and Sakshaug, 1998). As with nutrient runoff losses, combining soil aeration with manure applications has provided mixed results for the reduction of NH_3 losses. Gordon et al. (2000) saw no observable impact of soil aeration before or after dairy manure was broadcast. Placement of the aerator (prior or after manure spreading) and the angle of operation would likely impact the effectiveness of an aerator tool. Lawrence et al. (2008) found aeration after liquid dairy manure application, with the aerator set at its maximum angle, to be equally effective in conserving NH_4–N as chisel plow incorporation. Bhandral et al. (2009) aerated Italian ryegrass (*Lolium multiflorum* Lam.) before banding dairy slurry over the aeration slots and observed reductions in NH_3 volatilization of 18% in the spring and 15% in the summer, compared to nonaerated soils. Bittman et al. (2005) banded dairy slurry over injection slots and observed 46 to 48% lower NH_3 emissions than surface-broadcast manure.

Soil and environmental conditions, manure properties, and injector design impact rates of NH_3 emissions following manure injection. Containment of manure within the furrows is needed to maximize the reduction in emissions (Sommer and Hutchings, 2001). If compacted or wet soils prevent injection slot closure, manure can remain on the soil surface, increasing the quantities of NH_3 emitted. On ryegrass (*Lolium multiflorum* L.), Hansen et al. (2003) showed that reductions in NH_3 emissions were correlated with the depth and volume of the injection slot, but that the energy requirement was also greater for injector designs that provided greater reduction in NH_3 emission. Moseley et al. (1998) found that using a tine injector design with a narrow shank and a sweep at the base resulted in about 50% less NH_3 emission compared with using a wider shank with no sweep on arable land, probably because the sweeps increase mixing of manure with soil. In three experiments, Rodhe and Etana (2005) reported that manure injection on average halved NH_3 emissions relative to surface banding in grass-dominated ley in Sweden.

Banding of manure is used sometimes, especially in forage systems. Banding of manure on the soil surface can decrease ammonia volatilization in certain circumstances, relative to surface broadcasting, especially where a shoe is used that delivers manure below the crop canopy. This is due to a combination of small surface area and reduced wind speed over the manure that leads to higher atmospheric concentrations of NH_3 above the slurry (Sommer and Hutchings, 2001). Rochette et al. (2008) also reported that 14% of pig slurry broadcast onto perennial forages was intercepted by the crop canopy, which increased surface area for NH_3 volatilization, and this could be reduced by surface banding with a drag hose or trailing shoe. Where manure is banded on bare soil, NH_3 volatilization losses are significant (Sorensen, 2004). Rodhe et al. (2006) banded cattle slurry on predominantly red fescue (*Festuca rubra* L., cv. Rubin) and measured 40% less NH_3 volatilization compared to surface broadcast. Bittman et al. (2005) observed an average of 52% less NH_3 emitted, compared to broadcasting, when dairy slurry was banded directly behind an aerator into tall fescue. However, Sommer and Hutchings (2001) found that although surface banding of manure can decrease NH_3 volatilization where there is a crop growing to reduce wind speed over the soil surface, banding was not as effective as manure injection at decreasing NH_3 loss.

Greenhouse Gases

While injection of manure is generally expected to substantially reduce NH_3 volatilization, there is also a greater potential for greenhouse gas emissions, especially nitrous oxide (N_2O). The belowground placement of concentrated manure bands can lead to high rates of microbial activity and the depletion of oxygen, creating conditions favorable for the production of N_2O through denitrification (Flessa and Beese, 2000; Wulf et al., 2002b). Comparisons of N_2O emissions following manure injection and broadcasting are limited, but 15 to 300% greater N_2O emissions have been observed with chisel-type manure injections compared with surface application (Dosch and Gutser, 1996; Rodhe et al., 2006; Wulf et al., 2002b). These observed N_2O emissions following manure injection constitute only a small loss of plant-available N (<2% of total manure N), but N_2O is approximately 300 times more effective than CO_2 as a greenhouse gas (USEPA, 2005). For soil aeration in Italian ryegrass, Bhandral et al. (2009) measured no change in N_2O emissions compared with surface broadcasting. While there are currently no regulations for N_2O emissions from agricultural soils in the United States, the potential adoption of caps on greenhouse gas emissions could make N_2O emissions a more important consideration.

Table 3. Ammonia emissions 3 to 14 d following manure application relative to broadcast manure (Bittman et al., 2005; Curt Dell, USDA–ARS, personal communication, 2010; Gordon et al., 2000; Hansen et al., 2003; Lambert and Bork, 2003; Misselbrook et al., 1996; Morken and Sakshaug, 1998; Rochette et al., 2008; Rodhe et al., 2006; Smith et al., 2000; Sommer and Hutchings, 2001; Thompson and Meisinger, 2002; Weslien et al., 1998; Wulf et al., 2002b).

Method	Ammonia emission	
	Cropland	Forage
Chisel/knife injection	73% less	40% to ~100% less
Disk injection	58 to ~100% less	20 to 75% less
Pressure injection	57 to 64% less	62% less
Aerator		
Banded over aeration holes	No difference to 70% less	33% less
Pre/postapplication aeration	–	No difference
Tillage	50 to 100% less	–
Surface banding	No difference	14 to 40% less

Odor

Manure land application is the leading source of nuisance odor complaints in animal agriculture (Hardwick, 1985). A growing body of work documents the effects of alternative manure application methods on odor, as suburban sprawl and nuisance odor concerns become more widespread in previously rural areas. Conventional wisdom, repeated throughout the literature, acknowledges the benefits of manure incorporation for odor mitigation; however, rigorous studies documenting this effect are relatively scarce. Table 4 summarizes the findings of studies where odor emissions associated with various incorporation techniques are compared with broadcast spreading of slurry. As shown, a wide range of odor reduction levels have been reported.

Human sensory assessment (olfactometry) is the undisputed method of choice for odor quantification due to the vast array of odorant compounds, and unpredictable interactions. For example, >290 compounds have been identified in swine manure (Lo et al., 2008). Direct comparison of odor data among field studies is confounded by the broad array of application implements, field conditions (previous crop, residue, soil conditions), manure source and characteristics, weather, air sampling techniques, and odor quantification methods reported in the literature. Odor sample acquisition and sample numbers are a chief concern. Thorough human odor panel assessment is logistically demanding and expensive, and thus investigators are challenged to minimize the number of samples while maintaining adequate repetitions for statistical relevance. Use of static vs. dynamic-state flux chamber or wind tunnel devices, and the relatively small footprint of such units necessitate numerous sample locations as manure application equipment tool spacing is not consistent across the various implements. Acquisition of sufficient sample volume for off-site odor panel evaluation, and potential sample adulteration during storage, add additional uncertainties when laboratory olfactometry is used. Accordingly, recent research by Brandt et al. (2008) focused on methods to improve the reliability of field olfactometry observations, such that multiple real-time observations at a consistent downwind distance are obtained. These investigators have found decreasing dairy manure odor concentrations in the following order (α = 0.05): surface broadcast > aeration infiltration > surface + chisel incorporation > direct ground injection ≈ shallow disk injection > control, which closely followed laboratory olfactometry triangular forced-choice odor panel findings (r = 0.83).

Clearly, manure application methods can have a profound effect on odor emissions, particularly shortly after manure is applied when emissions are greatest (Pain et al., 1991). Volatile odorants can be mitigated by incorporation of manure into soil, so methods of application that directly incorporate slurry tend to reduce odor. As shown in Table 4, all incorporation methods typically reduced odor relative to broadcast spreading. Notably, Hanna et al. (2000) found emission reductions of >90% for some incorporation methods when odor concentrations were measured immediately after application. With time, odor reduction benefits from soil mixing diminishes and odor levels 1 d after application generally show less difference compared with surface application (Table 4). Moreover, it appears

Table 4. Reported odor concentration reductions for various manure incorporation techniques relative to surface broadcast application. Values listed indicate percent odor concentration reduction for indicated incorporation method vs. broadcast slurry application, for each study.

Method	Reduction in odor					
	%					
Brandt et al. (2008)—Dairy slurry on sod						
	Time after application					
	Preapplication	**<1 h**	**2–4 h**	**20 h**	**Avg.†**	
Direct ground injection	0	67	58	66	54	
Aeration infiltration	*−94*‡	33	56	14	16	
Shallow disk injection	0	63	72	61	55	
Surface broadcast + chisel	0	73	19	56	44	
Hanna et al. (2000)—Swine slurry on soybean residue						
	Spring 1997		**Fall 1997**		**Spring 1998**	
	Time after application					
	5 min	**24 h**	**5 min**	**24 h**	**5 min**	**24 h**
Row cleaner	56	*−10*	50	*−21*	97	25
Narrow knife	91	10	48	*−3*	88	59
Disk incorporate	81	68	25	*−2*	79	54
Chisel with sweep	75	60	37	*−16*	88	70
Chisel	76	*−8*	21	*−4*	82	66
Hanna et al. (2000)—Swine slurry on corn residue						
	Spring 1997		**Fall 1997**		**Spring 1998**	
	Time after application					
	5 min	**24 h**	**5 min**	**24 h**	**5 min**	**24 h**
Row cleaner	13	0	45	25	76	58
Narrow knife	51	*−27*	55	5	89	57
Disk incorporate	74	17	14	21	83	69
Sweep	88	13	33	34	92	81
Chisel	93	40	37	9	92	63

† Geometric mean of all applicable odor concentration observations, as reported by authors.

‡ Negative values (in italics) indicate odor concentrations higher than surface broadcast treatment.

that aerator-type applicators, which do not directly incorporate manure, are not as effective at reducing offending odors. For instance, Brandt et al. (2008) measured odor concentration following dairy manure application on sod and it decreased by 33% after 45 min.

Root Growth and Yield

Sawyer et al. (1990) reported NH_4 concentrations were high for 7 to 8 wk in vertical injection slits, and corn roots would not penetrate the injection slit during this time. Where a sweep was used, these conditions were drastically reduced or eliminated, and N was more evenly spread throughout the soil. However, Groot et al. (2007) either surface applied or injected manure into forage and reported greater yields where manure was injected. Therefore, either nutrients are reaching the roots outside the injection slit, the delay in root penetration does not affect yield in the long term, or a combination of the two. Groot et al. (2007) also reported greater N recovery from injected manure than surface applied, probably due to lower losses via NH_3 volatilization. Ball-Coelho et al. (2006) surface applied or injected swine manure to corn and measured greater N recovery for injected (59%) than for surface-applied (41%) manure. Across several sites, Russelle et al. (2008) reported greater N uptake, and therefore corn yield, with injected compared to surface-applied dairy and swine manure, which they attributed to greater capture of NH_3–N when manure was injected. Sutton et al. (1982) also reported that corn grain yield was 14% greater for injected vs. surface-broadcast swine manure. Russelle et al. (2008) were also able to predict plant available N to corn more reliably when manure was injected, and they attributed this to weather having a more variable effect on NH_3 volatilization for surface-applied manure. The summary data in Table 5 show the variability of results and the lack of values for several combinations of manure application and crop type demonstrates how much work remains to be done. For example, surface banding, aeration, and high-pressure injection have mainly been evaluated on forage systems, while chisel and disk injection has been mainly evaluated on row crop production. In most instances, technologies that place manure below the soil surface increase yield due to greater NH_3 capture, but there are some instances of decreased yield, especially in forages where there can be damage to roots and canopy.

Root damage to forages may be a concern with some implements, as spacing between injectors varies and greater damage to forages would be expected where there were more injectors cutting roots. For example, Rodhe et al. (2006) used an injector with 25-cm spacing between disks, while Burcham et al. (2008) had a spacing of 75 cm for his injector. Rodhe et al. (2006) reported the cutting of the injection disks could decrease the yield in some situations relative to a surface banding of manure. Therefore, greater spacing of injector disks should be advantageous when injecting manure into forages to minimize forage damage.

Gordon et al. (2000) found that combining soil aeration with broadcast surface manure applications decreased forage yields predominated by timothy (*Phleum pratense* ssp. *pratense* L.) compared with manure applications without soil aeration. Shah et al. (2004) applied manure to orchardgrass and also found that yields where soils had been aerated were only 81% of those without aeration. Bittman et al. (2005) reported that aeration of tall fescue and orchardgrass and banded manure over aeration slots either increased or decreased yield relative to a surface manure application. These inconsistent effects may have been due to different weather conditions, soil moisture, and time of year when aeration was conducted (Bittman et al., 2005).

Where surface banding of manure is done to growing tall fescue and NH_3 volatilization is reduced, the greater NH_3 capture translates into increased yield (Bittman et al., 1999). Surface banding of slurry on forages is now widely practiced in Europe, as it provides better yield responses than broadcasting (Bittman et al., 2005). However, Sorensen (2004) applied dairy slurry preplanting to spring barley and ryegrass (*Lolium perenne* L., cv. Borvi) and reported that N recovery was greater for slurry mixed with the soil (46%) and injected (42%) than when it was surface banded (22%).

Conclusions

There is now a wide variety of new technologies available for manure management in no-till and forage lands that offer improved manure N use efficiency and water and air quality benefits, relative to surface application of manures. Placing manure below the soil surface decreases odors, and captures more manure N that often increases yields relative to surface applications, although mechanical damage to forages can decrease yields in some cases. Depending on conditions, >85% of total NH_4–N can be lost as NH_3 from surface-applied manure within 24 h. Therefore, tillage has to occur immediately after manure application to effectively capture N. Soil aeration followed by manure application does not consistently decrease NH_3 volatilization or nutrient losses in runoff. Though a range of aeration equipment is available, there is an insufficient number of studies to identify when aeration may work and when there will be no benefit. Surface banding of manures offers promise for reducing NH_3 volatilization where

Table 5. Yield differences among alternative manure application methods and surface broadcasting manure.†

Method	Difference in yield relative to broadcasting			
	Corn	Soybean	Small grain	Grass
Chisel injection	2% less to 14% greater	4% less to 16% higher	0%	–
Disk injection	–	–	0–10% greater	–
Pressure injection	–	–	–	8% greater
Aerator	–	–	–	19% less to 36% greater
Surface banding	–	–	–	0–21% greater

† Summarized from Hanna et al. (2000); Smith et al. (2000); Morken and Sakshaug (1998); Shah et al. (2004); Bittman et al. (1999, 2005); Butler et al. (2008); Gordon et al. (2000); Sutton et al. (1982).

there is a standing crop, such as application to forages, especially where the ground is too stony for manure injection. From the studies available, manure injection seems to offer the most promise in terms of reducing NH_3 volatilization in no-till and forages, and this can increase yield where N is limiting, and decrease odors and nutrient and sediment losses in runoff. However, as for aeration devices, there is a wide range of manure injection equipment available and not enough studies have been conducted to evaluate which are most beneficial in different situations. For example, more soil disturbance may be acceptable for preplant manure injection for row crops than for manure injection into established forages, which may be damaged. Although it is now possible to use these technologies to improve N recovery and decrease nutrient losses in runoff and odor problems, surface broadcasting remains the predominant method used for liquid manures, as it is quick and cheap. There are great opportunities to improve manure management in no-till and forages if the economic hurdle can be overcome.

Knowledge Gaps and Research Needs

As mentioned above, more studies are needed to look at all available technologies for improving manure management in no-till and forages. Several key issues need to be addressed:

- Studies need a standard protocol to ensure they are directly comparable, similar to the National P Research Protocol, which was developed in the United States for standardizing rainfall simulations.
- Many studies only report one component, such as NH_3 volatilization. Comprehensive research is needed that includes N, P, and sediment losses in runoff, N leaching, NH_3 volatilization, odor, and yield.
- New and emerging contaminants should also be considered, such as pathogens and endocrine disruptors, which may be kept in soils and out of surface waters and the food chain by improved manure placement in the soil.
- Detailed information on N and carbon cycling and stratification, especially in the long term, as not much is known on how these will be affected.
- Anecdotal evidence suggests manure injection is slower and more expensive than surface broadcasting, but there is a lack of published data. Economic assessment is essential, including value of saved N and energy and time costs, as this will be essential for implementation.
- Many other questions remain, such as ideal depth and placement for injection for different soils and crops; are starter fertilizers needed, especially if manure injection bands are far apart?

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