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Achieving net zero dairy farming

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Optimizing manure and slurry application from intensive dairy farming operations

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1 Introduction

An important benefit of manure, long known and exploited, is the concentration of nutrients by confined animals that can be collected and spread onto cropland to improve crop production. Integrated farming of livestock and crops was widely practiced long before the benefits of transferring manure nutrients to crops were scientifically understood. The lack of adequate manure for expanding agriculture led in the late 1800s to the collection and importation of large quantities of bird guano from vast deposits in South America, which ultimately motivated the invention of lower-cost, more easily accessible manufactured nitrogen (N) fertilizers using the Haber-Bosch process, and the discovery of mined phosphorus (P), potassium (K), and other nutrients for use as fertilizer. As fertilizer availability increased, the logistical

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disadvantages of manure management became more widely recognized than its value as a soil amendment, and manure was relegated, on many farms, as an unavoidable waste to be expediently discarded. There has often been insufficient regard to the possible benefits of manure as a soil amendment or to manure management practices that could mitigate widespread contamination of surface (esp. P, pathogens) and ground water (esp. nitrate (NO_3)) and of soil nutrient overloading. The impacts of manure on air quality, via atmospheric deposition of nutrients into oligotrophic ecosystems, and of fine particulate formation on human health are also often overlooked.

The growing interest in strategic manure use has stemmed less from an increasing appreciation of its intrinsic value and economic benefits than from growing concern by the public, and mounting scientific evidence of environmental degradation on farmland and surrounding ecosystems. These have, in turn, led to regulations such as application limits under the nitrate vulnerable zones (NVZs) and ammonia (NH_3) emission limits (National Emission Ceilings) directives in the EU, and the P indices imposed in several US jurisdictions. There is an inclination to overapply manure because it is free and more unwieldy to transport and apply than purchased fertilizer. The current coincidence of anxiety by farmers about loss of soil organic matter (SOM) and the need for preservation of soil health and by the public about our changing climate has positioned increased soil organic carbon (SOC) and the use of manure carbon (C) as possible redeemers of society's collective bad behaviour. From small to large, many farmers now see increased SOM as a tool to elevate crop productivity and improve land value and to serve as a possible revenue stream under remunerative C sequestration schemes. Counterposed are the inevitable emissions of nitrous oxide (N_2O) from applied manure, both directly after application and indirectly as secondary emissions from deposited gaseous NH_3, and particulate ammonium (NH_4) or leached NO_3, plus nutrient loss in run-off resulting in water quality degradation. The loss of methane (CH_4) from stored slurry manure, which contributes both to global warming and to tropospheric ozone formation, must also be considered (Sampedro et al. 2023).

Emission rates of NH_3 are determined by conditions at the manure–atmosphere interface, which are difficult to measure and are rarely done, especially in *in situ* studies. Emitted NH_3-N is mixed in the atmosphere and transported by air (Asman et al. 1998). Some gaseous NH_3 is deposited on nearby soil or vegetation depending on concentration gradients (referred to as dry deposition), but the majority is transported for one to many kilometers, mostly as secondary fine particulates and aerosols formed in the atmosphere by reaction of NH_3 with acid gases, such as NOx, SOx, Cl, and organic acids (Bittman et al. 2014b) (Fig. 1). These N-rich fine (<2.5 μm) particulates are deleterious to the health of humans (and animals) because they are capable of penetrating deep into lungs and causing cardio-pulmonary illnesses (Wyer

Figure 1 Air pollution caused by fine particulates containing ammonium from agricultural sources in south-coastal BC, Canada. Panel on the left depicts high-visibility wintertime conditions due to low ammonia emissions. The panel on the right shows the same view in mid-summer, where ammonia-based fine particulates reduced visibility (Barthelmie and Pryor 1998). Photos by S. Bittman, Agriculture and Agri-Food Canada.

et al. 2022). When these particles are deposited (wet deposition), usually at a distance from the source, they can acidify soils and harm oligotrophic ecosystems such as alpine meadows, lakes, and bogs (Clark et al. 2021).

Agriculture is the primary source of atmospheric NH_3 in industrial countries with large agricultural sectors and, unlike other air pollutants, NH_3 has been trending higher in recent decades due to the expansion of livestock production and increased application of NH_3-based fertilizers (Wyer et al. 2022). Emissions of NH_3 must be reported by all UNECE (United Nations Economic Commission for Europe) parties in 'ground up' emission inventories under the Convention for LongRange Transport of Air Pollution (CLRTAP). Methods for mitigation of NH_3 losses from agricultural sources, including land spreading of manure, in consideration of all reactive N species, are suggested for the UNECE in an official Guidance Document (Sutton et al. 2022), and global guidance is being developed under the International Nitrogen Management System (INMS; https://www.inms.international/).

Since manure sources have concentrated and expanded in past decades, often in ever larger animal facilities and livestock-intensive regions, it has become increasingly important and perhaps daunting to manage manure strategically (Kleinman et al. 2022). Whereas there are aspirations now towards processing manure so it can be transported and returned to distant cropland and remote cropping regions, and towards production of commercial soil enhancers such as compost, it remains the simplest approach for many farmers to use manure on their own operations to replace fertilizer and improve/maintain soil productivity and health. But using manure to replace fertilizer has proven to be challenging, all the more so in crowded landscapes with growing populations, especially around cities, and where there is competition for land, space, and water and ever-increasing concentration of nutrients. In many countries, the need for intensive agricultural production, including dairy, in such regions is forcing incentive and invention (Bittman and Hunt 2024).

The objective of this chapter is to describe progress towards the use of manure for replacing commercial nutrients and enhancing SOM, in the face of longstanding and modern obstacles that include logistics and unpredictability, and avoiding environmental harm. The intention is also to consider novel approaches that may be needed for further advances. For this chapter, manure consists primarily of excreta (faeces, urine) and bedding materials, which are handled either as a liquid (called slurry) or solid (referred to as farmyard manure or FYM).

2 Factors affecting dairy slurry composition

Animal manures and slurries contain multiple elements in a variety of chemical forms. Common elements in dairy manure and slurry include N, P, C, calcium, K, sulphur, and zinc; however, this chapter will focus on N, P, and C. The forms and concentrations of these elements can be altered by a variety of factors, including animal diets and manure handling, processing, and storage (Ouatahar et al. 2021). For example, the C content of manure from 22 conventional and organic dairy farms in Texas ranged from 12% to 45% C (dry matter basis), depending on the type of forage provided (hay, pasture, haylage, maize silage), the use of bedding materials, storage type (e.g. stacking pad, pit, roofed storage, lagoon, windrow), and physical composition (He and Waldrip 2015). Slurry from dairy farms in coastal British Columbia (BC), Canada, averaged 2.5% C on a wet basis, with a C:N ratio of ~9.8.

Dairy manure C is typically dominated by aromatic (e.g. from lignin and tannins) and aliphatic (long chain, C-rich) biopolymers (e.g. waxes, suberins, and cutins) as shown by C-13 nuclear magnetic resonance (^{13}C NMR) spectroscopy (He and Waldrip 2015). This is because the more soluble C compounds (amino acids, simple sugars, and low-molecular weight organic acids) contained in feed are preferentially consumed during cattle digestion, leaving behind more complex, less easily degraded C compounds (He et al. 2015, He et al. 2009). Composting of manure leads to further microbial consumption of degradable carbohydrates and to accumulation of less- degradable proteins and phenolic and carboxylic forms of C in the compost (Liang et al. 1996).

On a fresh basis, dairy slurry usually varies from about 5–7% dry matter with about 0.25% (2.5 g kg^{-1}) total N; 0.13% TAN (total ammoniacal N = NH_4-N plus NH_3-N); and 0.05% (0.49 g kg^{-1}) total P. Typically, the TAN to total N ratio is 60–70% (higher with high protein diets), and the total N:total P ratio is 5:1 to 6:1 (e.g. Bittman et al. 2011). This means that a 10 000-litre tank of slurry contains just 25 kg of total N (of which 15-18 kg is readily available TAN) and about 5 kg of P (only a portion of which may be plant available), illustrating a key logistical challenge of using manure nutrients to replace chemical fertilizers. With a pH of around 6.8–7.2, there is a significant tendency for the NH_4-NH_3

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equilibrium to shift towards the production of gaseous NH_3; this promotes NH_3 losses from manure exposed to the atmosphere, especially under hot, windy conditions (Sommer et al. 1991). Thus, the C:N ratio of fresh dairy slurry is lower than farmyard manure (FYM) due to loss of volatile NH_3 in storage.

Nitrogen is excreted in urine as urea, which is rapidly hydrolysed to NH_3 and NH_4 (TAN) by the ubiquitous urease enzyme excreted in faeces. Separating urine from faeces at the time of excretion will preserve urea and slow the formation of TAN. This has been attempted, but is difficult to accomplish in housing, although this separation occurs naturally on pastures where NH_3 emissions are typically much lower than from housing. The organic N in slurry is mainly from excreted faeces, consisting largely of undigested protein bound to undigestible fibre and lignin and from other organic materials such as discarded or soiled feed and (low N) bedding materials. Farmers may also occasionally recycle spoiled feed into manure storages.

Ideally, manure application rates are informed by the content of TAN, N, and P. Unlike fertilizer, however, manure does not come with a ready analysis and because sampling stored manure is often very difficult (Ni and Lim 2022), testing is typically done infrequently. Although sampling from a manure pit after agitation or from the manure tanker itself is simpler, awaiting lab results would inevitably delay spreading. Furthermore, inaccuracies can arise due to inter-lab variability in analytical methods and the problem of subsampling heterogeneous material. Instead, application rates can be determined using *in situ* tests for TAN; test results can be validated with laboratory testing post-spreading, although this is not commonly done. A long established *in situ* tester for TAN concentration in slurry is the Nova/Agros meter (AGROS NOVA meter for liquid manure (novanna.co.uk)), which converts NH_4 from a manure sample placed in a sealed container to N_2, which is then measured using a pressure gauge attached to the container (Van Kessel and Reeves 2000). Concentrations of total N and P can then be estimated from previous laboratory-based manure analyses, because ratios of TAN:Total-N and Total N:P in manure slurry are relatively stable on farms under consistent feeding and manure management practices. Real-time analyses using selective ion sensors and near infra-red spectrometry are under development but not yet widely done (Reeves 2007; Feng et al. 2022; Piepel and Olfs 2023). These tools are used for liquid manures (slurry) but not solid manures, which contain less TAN and which are also especially difficult to sample before spreading.

Importantly, while total P in slurry can be estimated from ratios of total N:P, total P is not always a good predictor of plant-available phosphate. A range of inorganic and organic (bonded to C groups) P compounds can be found in manures and slurries. Inorganic P compounds include phosphate (HPO_4^{2-} or $H_2PO_4^-$ at the pH range of most samples), polyphosphates (chains of three or more phosphate groups linked by anhydrous bonds), and pyrophosphate (polyphosphates with two phosphate groups). Phosphates in dairy manure and slurry can originate directly from dietary mineral additives or from the hydrolysis of organic P compounds in feed during digestion. Pyrophosphate and polyphosphate in manures, including slurry, may come from undigested dietary plant material or from excreted rumen microbes, for which they are P storage compounds (Toor et al. 2005). Organic P compounds are grouped by bonding with C groups into orthophosphate monoesters [one C group per phosphate, linked by oxygen (O); P-O-C], orthophosphate diesters (two C-groups per phosphate, C-O-P-O-C), and phosphonates (direct C-P bond, without O). Orthophosphate monoesters include phytate (*myo*-inositol hexaphosphate), a P storage compound in grain and plant material (e.g. maize), and simple sugar phosphate such as glucose-6-phosphate. Orthophosphate diesters include so-called 'biological' P compounds, such as RNA and DNA, and phospholipids and lipoteichoic acids in cell walls of plant materials from feed and in rumen microbes. There is a range of phosphonate compounds, but the compound most detected in slurry and manure is 2-aminoethylphosphonic acid (2-AEP, also called ciliatine), from the cilia of rumen protozoa (Toor et al. 2005).

3 Dairy manure production in Canada

Dairy production in Canada is year-round (aseasonal) by animals that are totally or largely confined because of prolonged winters and consistent year-round milk demand. This is in marked contrast to seasonal beef cattle production in Canada, where calving occurs mainly in spring. Beef cattle are grazed in summer; in winter, they are housed (winter dry lots) or sometimes grazed with bale-feeding (Kelln et al. 2012; Chen et al. 2017). Eventually, cattle are moved to large feedlots for finishing for market. In countries where dairy animals are kept largely on pastures, such as Ireland and New Zealand, milk production is more seasonal than in Canada, with most milk produced on fresh grass in spring and much less in winter. From the time of excretion to land application, emission of NH_3 from manure is a critical loss pathway for N from dairy farms. Based on unit food protein produced, emissions from dairy production are similar to poultry (meat) but much lower than beef or pig production (Bittman et al. 2017). In Canada, 85% of large dairy farms with an average of 195 lactating cows handle manure as slurry compared to only 64% of farms averaging 40 lactating cows. Dairy farms in Canada are often family-owned operations with most milk cows kept on farms with less than 75 milking cows (VanderZaag et al. 2023). There has been a trend towards increasing farm size and milk production (Sheppard et al. 2011a), while total cow numbers in Canada have decreased over the past 20 years, thanks to increasing milk production per lactation, achieved by improved genetics and feeding practices (Bach et al. 2020).

Precise feeding is managed by frequent feed testing and adjusting rations for different stages of growth and periods of lactation, with particular attention to digestible fibre and protein attributes and to P concentration, in order to maximize milk production at low feeding costs. Currently, N use efficiency (NUE) (N exported as milk and meat/N consumed by cattle) for dairy cows is about 25–30% (Pogue et al. 2025); the remainder of the N is excreted in faeces (40%) and urine (60%). As mentioned above, the animal diet will directly affect both the forms and concentrations of P compounds in manure. Dietary P is essential for milk synthesis, and cows with inadequate dietary P may have reduced milk production or adverse health effects, e.g. due to mobilization of P from bone (Wu et al. 2000). The P concentration of forages and grains can vary widely, so commercial P supplements are often added to the diets of lactating cows to ensure sufficient dietary P (Toor et al. 2005; Duplessis et al. 2021). This, in turn, will affect manure P concentration, with higher total P concentrations in manure from animals with higher dietary P (Toor et al. 2005). Dietary P will also alter manure P forms; e.g. manure from animals with higher dietary P from supplementation contains more phosphate (Toor et al. 2005; McDowell et al. 2008). However, diets high in phytate from grains do not result in manure with higher phytate concentrations likely due to hydrolysis of phytate to phosphate during digestion in the rumen (McDowell et al. 2008).

In Canada and elsewhere, there has been a shift away from tie-stall barns with solid manure to free-stall and loose housing barns where manure is handled as slurry that is collected several times per day by scraping or washing. In 2006, 51% of dairy farms were handling manure as slurry, and this proportion has since increased with farm size (Sheppard et al. 2011a). About 21% of TAN is emitted as NH_3 from dairy housing and 5.5% from storages, which is a significant loss of available N that effectively decreases the N:P ratio of applied slurry (Sheppard et al. 2011b). Many measures are used to minimize N losses (especially NH_3) from animal facilities. The slurry manure is stored over winter for as long as 6–8 months in concrete or steel tanks or large (usually lined) lagoons. Unlike in European countries where there is concern about limiting NH_3 emissions into the atmosphere, few storage facilities in Canada have covers, although some storages are under roofs to keep out precipitation and ensure sufficient capacity, which is particularly important in rainy years. Despite lack of covers, NH_3 emission from dairy storages are relatively small because the slurry in storage often forms a surface crust and because of cold winter-time temperatures (Sheppard et al. 2011b). Emission of NH_3 from manure, from the time of excretion to land application, is a critical loss pathway for dairy farm N. Of the excreted N by dairy animals, 27% is lost by land spreading manure, which is about 51% of all NH_3 losses on dairy operations.

The bedding used in dairy barns is mainly straw in grain-growing regions and wood chips or sawdust in regions where those products are abundant.

On some farms, sand bedding is used to optimize animal health (Singh et al. 2020). Much of the sand is recovered from manure by filtration prior to re-use, but sand is hard on manure handling equipment, which often requires more maintenance. Some farmers also recover organic solids from slurry for use as bedding after solid/liquid separation, followed by processing in a tumbling drip composter (Ackerman et al. 2018). Devices such as the BeddingMaster (https://mavasol.com/en/solutions/manure-management/products/beddingmaster) can be used to facilitate this process. Surplus recovered bedding is supplied to nearby dairy farms or to horticultural operations for use as mulch (Franzluebbers et al. 2021) or as a soil amendment; with its high C:N ratio (31.2), recovered bedding can be preferable to raw manures, such as poultry litter (C:N of 6.3) or even cured compost (C:N of 22.9), because of lower N leaching risk (Zhang et al. 2019). The choice of bedding materials can also substantially alter manure P forms and concentrations, as can subsequent manure treatment, such as composting. For example, straw and wood products can add phosphate and phytate (Noack et al. 2012; Cade-Menun et al. 2015), and separated solids used as bedding material can have much higher total P concentrations and lower N:P than the original dairy manures used to produce the materials (Ackerman et al. 2018). Composting can alter manure P composition compared to faeces, increasing both phosphate concentration and organic P species associated with the microbes involved in decomposition (Toor et al. 2005), although Hansen et al. (2004) suggested that the P forms in solid manure and lagoon manure were similar.

4 Using dairy manure and slurry for crop fertilization

4.1 Applying manure/slurry to fields

A primary goal of applying manure on cropland is to replace and perhaps obviate the need for chemical fertilizers. The logistics of spreading both slurry and FYM are complicated because of their low nutrient concentrations and the large quantities of material that must be handled and transported (Harrigan 2010). The drier and lighter FYM is often broadcast onto soils, with incorporation via tillage helping to increase the availability of nutrients to crops and minimize runoff losses (Kumaragamage and Akinremi 2018). However, tillage cannot be conducted on perennial field crops or under no-till systems. Manure that is not fully incorporated into the soil leaves high concentrations of phosphate and phytate at the soil surface (Cade-Menun et al. 2015), rendering it prone to loss from the field and contamination of surface waters, e.g., due to overland flow and even wind transport. There are some injection tools for soil application of poultry litter, but these methods are not widely used and are unsuitable for clumpier cattle FYM (Kulesza et al. 2016; Landry et al. 2011).

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Slurry applications require hauling massive quantities onto fields over a short time window. All manure tanks are heavy, particularly rapid, self-loading vacuum tanks. As a consequence, soil compaction can be a common problem caused by slurry manure applications, especially on wet, poorly drained and/or fine-textured soils. Tramlines (travel on set tracks) used for applying fertilizer and pesticides on arable crops are rarely used for manure spreading for logistical reasons (see Mederle and Bernhardt 2017). Flotation tires can reduce the risk of soil compaction, but they are expensive and not suitable if extensive road travel is required, although some tractors can extend tire wear by adjusting tire pressure between road transport and field travel. Other measures to facilitate the spreading of slurry while preventing soil compaction include umbilical (dragline) systems, where long flexible hoses are used to transfer manure from stores to fields, obviating the need for heavy tanks. Only very large farms can afford this expensive equipment; smaller operations may engage contractors, where available. Farms with large volumes of manure (e.g. large operations with shallow, uncovered lagoons in high rainfall areas) may install underground pipes to rapidly move manure from stores to fields. Others collect manure in temporary flexible storage placed near crop fields to hasten spreading during critical application windows. The ability to spread manure rapidly is important when labour is limited and/or expensive and the application time is constrained by short seasons or by inclement weather.

The most rapid and least trouble-prone method of spreading slurry is by broadcasting (e.g. splash-plate applicator), especially on small family farms with limited resources. About 80% of dairy farms in Canada spread manure by broadcasting (in 2005). However, slurry applied via broadcasting is prone to substantial N losses by NH_3 volatilization and associated odours, which may restrict applications near residential areas. Furthermore, broadcast manure tends to be applied unevenly, particularly in windy conditions, and is more likely to contaminate protected areas or waterways due to drift. Some European countries (The Netherlands, Denmark) have banned slurry broadcasting to reduce NH_3 emissions into the atmosphere.

4.2 Determining manure application rates

Like fertilizer, manure must be applied at crop-appropriate rates, which is aided by *in situ* testing methods (see above). However, the availability of manure nutrients, especially N, is less predictable and less consistent than fertilizer, because of variable mineralization rates of the organic N fraction and, especially, the propensity for substantial NH_3 loss by volatilization in the hours and days after application. Manure and slurry application rates are most often based on crop N requirements, which will oversupply P because the ratio of N:P in manures and slurries does not match crop nutrient requirements

(Kumaragamage and Akinremi 2018). This ratio can be improved by using a separated dairy slurry rather than a whole dairy slurry, which contains a lower P:N relative to whole slurry (Table 1). Separation efficiency varies greatly with method and manure type (Möller et al. 2002).

Loss of NH_3 via volatilization is highly variable and can depend on many factors, including weather (temperature, rain, wind, relative humidity, sunshine), soil properties (porosity, water content, cation exchange capacity, pH), and manure composition (NH_3 and dry matter concentration, pH, viscosity) (Sommer et al. 2003). As well, crop residue or a living crop canopy may, paradoxically, affect emissions in opposite directions – on the one hand, emissions decrease when living plants or crop residues at the soil surface reduce airflow, incident solar radiation and soil surface temperatures, and facilitate absorption of NH_3 into leaves (Sutton et al. 1993); on the other hand, emissions increase when living plants or crop residue prevent manure from reaching the soil surface where NH_4 ions can be adsorbed.

Various low-emission applicators, some with a span >10 m for rapid application, have been developed to conserve manure N and reduce deleterious emissions. Two applicator types are particularly rapid and require little additional power: trailing hoses, which hang loosely at or near the ground surface, and trailing shoes, which float directly on the soil surface. Applicators that penetrate the soil and require more power include shallow injection with open slots (<10 cm deep), and deep- or closed-slot injection (>15 cm deep), where no manure is left exposed to air. In each case, the manure stream from the tank is divided with a chopper-distributor into multiple smaller streams that feed into individual emitters spaced across a draw bar. The chopper is designed to divide the flow evenly (ideally CV <10%) and prevent blockages in the smaller hoses, which is critical for efficient operation of low-emission applicators. A less refined tool with no active divider, consisting of a simple manifold assembled with PVC pipes, can be home built; pipes are kept rather large (approx. internal diameter of 7–10 cm) to avoid blockages and, hence,

Table 1 Properties of whole dairy slurry and liquid fraction separated by settling in a two-stage lagoon system, averaged over 6 years, in coastal BC, Canada

	Whole slurry	Liquid fraction
Dry matter, %	5.9	1.6
TAN, g kg^{-1}	1.31	0.95
Total-N, g kg^{-1}	2.54	1.45
TAN:Total-N	0.52	0.66
Total P, g kg^{-1}	0.49	0.15
Total N:P	5.18	9.67
pH	7.0	7.6

are spaced further apart. Even less ambitious, the pipes may be designed to terminate above the canopy and used as low-trajectory broadcasting devices.

4.3 Can soil-applied dairy manure replace commercial fertilizer?

To begin addressing this question, we compared the effect on grass yield and N uptake of conventionally applied (broadcast via splash plate) slurry, slurry applied by trailing shoe (also called a drag-shoe), and commercial fertilizer (Bittman et al. 1999). Drag-shoe application places surface bands of manure on the soil surface. The study was conducted over 3 years in a Mediterranean-type maritime climate on a stand of perennial tall fescue (*Festuca arundinacea* Scheb.). Figure 2 shows N uptake of grass after application of commercial fertilizer (curved lines) and slurry at equivalent rates of mineral N in spring, summer, and autumn. Nitrogen uptake response to broadcast slurry was variable, especially in the summer, but the response to drag-shoe applied slurry was consistently similar to the commercial fertilizer. Over the nine campaigns, total N recovery relative to the quantity of applied mineral N averaged 58% for fertilizer, 53% for drag-shoe applied slurry and 39% for broadcast applied slurry; thus, 14% of applied mineral N in slurry was conserved with low emission application relative to broadcast application. Of the total manure N applied, 27% and 20% was recovered after drag-shoe vs broadcast slurry application, respectively; the remainder was either lost to the environment or remained in soil. Low-emission application was superior but perhaps not economically attractive based on the value of N, especially if the farm has an abundance of manure. However, the added benefits of uniform application, less soil acidification than NH_4-based fertilizers, potentially less P loading, climate and NH_3 mitigation (less fertilizer consumption, less secondary N_2O), reduced odour (Lau et al. 2003), and better aesthetics (see Fig. 3) may encourage farmers to consider adoption. Although not measured here, NH_3 emission reductions of up to 60% are attributed, on average, to trailing shoe applicators (Webb et al. 2010; Misselbrook et al. 2022) due to reduced exposed area of the banded manure and to less slurry deposited on crop residue or stubble. Delayed application of fertilizer and slurry, which often occurs on farms due to weather or other factors, affected N uptake only in autumn when growing conditions decline.

The banded slurry gradually soaks into the soil, where the dissolved TAN is adsorbed. To facilitate infiltration of slurry into the soil, reduce NH_3 loss, and improve N recovery, we developed an applicator that bands slurry with trailing shoes directly over vertical pockets formed by rolling tines (20 cm deep at 19 cm × 47 cm spacing). These pockets can accommodate up to 26 t ha^{-1} of slurry, which is similar to that of slurry application via slot injection. While this is lower than typical slurry application rates in Canada (40–60 t ha^{-1}), the slight twist of

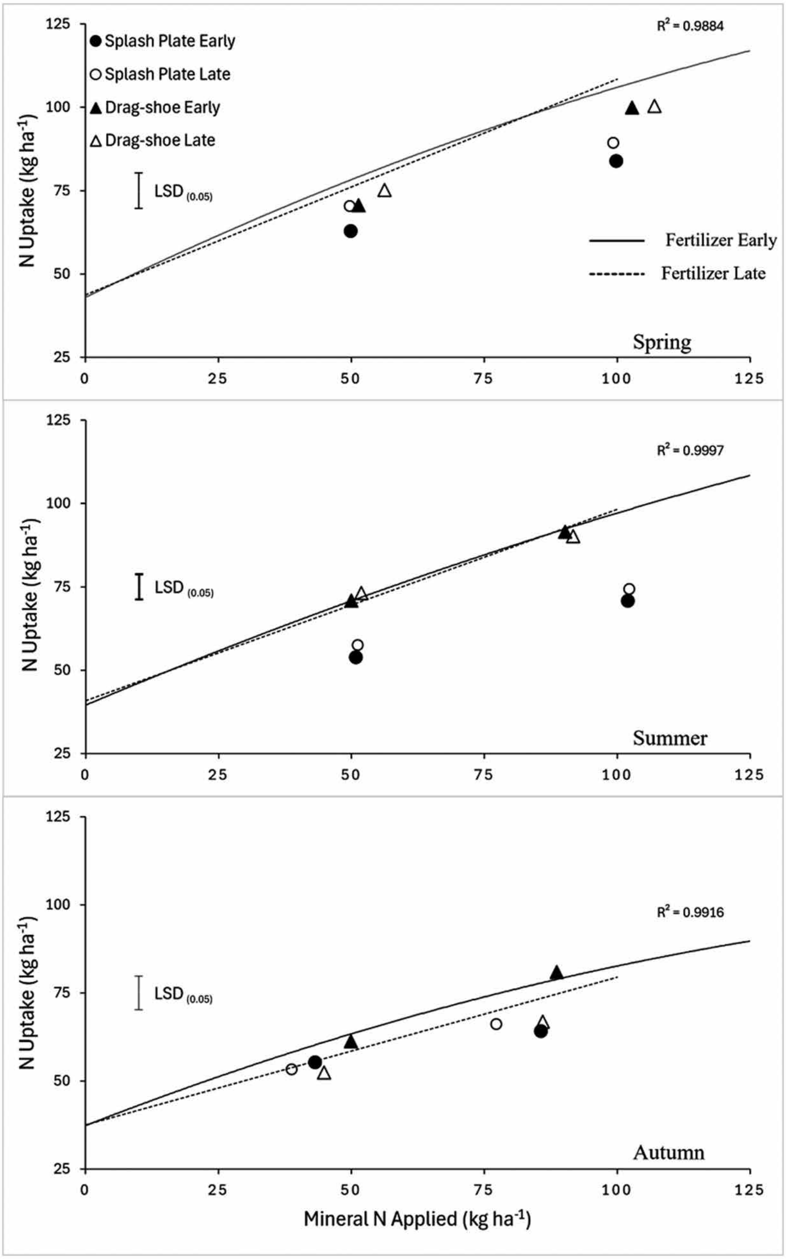

Figure 2 Nitrogen uptake (herbage yield x N concentration) by tall fescue as affected by NH_4-NO_3 fertilizer (lines) and dairy slurry spread with splash plate (circles) and drag-shoe applicators (triangles). Applications are either early (at beginning of growth) or late (7–10 days later) in spring, summer, and autumn. Data are means across 3 years (1994–1996). Source: Adapted from: Bittman et al. (1999).

Figure 3 Slurry applicator with surface banding over rolling tines in south-western BC, Canada. Photos by S. Bittman and D.E. Hunt. Agriculture and Agri-Food Canada.

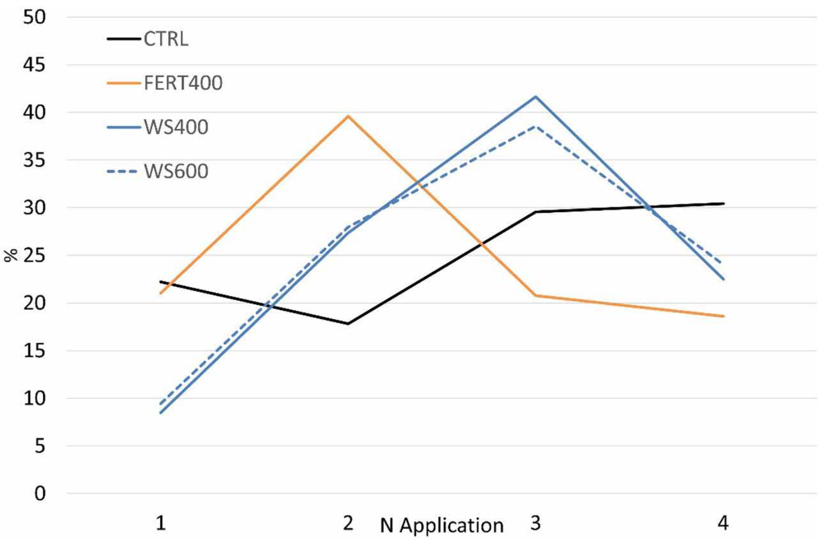

Figure 4 Relative loss of N_2O after applications of dairy slurry at low (WS400) and high (WS600) rates and NH_4-NO_3 fertilizer (FERT400) and Control (CTRL) on grass in April (1), June (2), August (3), and Sept. (4). Emissions are percent of annual, averaged over 5 years. Lowest emissions for slurry followed the first application due to cool soils. Emissions from chemical fertilizer occurred earlier than slurry due to the presence of NO_3 in the fertilizer but not in the slurry. Source: Adapted from: Hunt et al. (2019).

the tines is also designed to loosen the soil and further enhance infiltration of thinner slurry fractions with dissolved NH_4 (Fig. 3).

Field measurements using integrated horizontal flux or semi-closed chambers showed 46–48% less NH_3 emissions with the rolling tine applicator compared to broadcasting, although N uptake by grass was increased by only 14% (Bittman et al. 2005b). Dell et al. (2012), using the same commercial implement, reported NH_3 reductions of 30–70% over 3 years but no agronomic benefit over broadcasting. Similarly, Sherman et al. (2021) reported a 52% reduction in NH_3 emissions by application with rolling tines compared to broadcasting, which was less than reduction by shallow injection but greater than with banding; treatment effects on yield were inconsistent. Sherman et al. (2021) did report more N_2O emissions using rolling tines than broadcast manure but less than shallow injection, cautioning about environmental tradeoffs. Inconsistent results of the rolling tine relative to broadcasting may be related to higher manure dry matter or wet soil conditions that reduce the capacity for enhanced slurry infiltration.

Of note, the rolling tine can be used on stony and sloped land where it can reduce surface run-off of dissolved P and suspended solids after manure application relative to broadcasting (Table 2), especially in uncompacted and unsaturated soil (van Vliet et al. 2006; Johnson et al. 2011). In contrast to the rolling tine, shallow, open furrows by shallow injection may facilitate manure run-off on sloped fields (farmer observation). The rolling tines may also reduce preferential flow of slurry in soils with substantial macropores, thereby mitigating the risk of microbial and nutrient contamination of water bodies (Lapen et al. 2008).

Manure application timing can reduce emissions of NH_3 (and N_2O^- see below), but care is required to avoid environmental trade-offs. Strategic reduction in emissions by timing has been called Application Timing Management System and is recognized by the UNECE as a mitigation method for NH_3 with some caveats (Bittman et al. 2014b). For example, applying slurry in cool, moist weather (e.g. spring vs summer) can significantly reduce NH_3 emissions and improve N-uptake (Lalor et al. 2011; Fig. 1), but might also be associated with a higher risk of leaching and run-off. Emissions of N_2O could also be reduced by spreading manure in early spring (when soils are cool) and avoiding late spring and early summer applications when soils are warm and

Table 2 Effect of soil aeration with rolling tines in uncompacted soil (Holland Equipment Ltd., Norwich, ON) on runoff volumes, and loadings of suspended solids and dissolved reactive P after autumn application of dairy slurry in south coastal BC, Canada

	1998–1999 (high rain)		2001–2002 (low rain)	
Parameter	Control	Aeration	Control	Aeration
Runoff amount (L)	10 460	1990	3550	1890
Suspended solids load (kg ha^{-1})	130	40	400	210
Dissolved reactive P load (kg ha^{-1})	0.71	0.03	0.65	0.11

Data from the driest and wettest of four winters are shown in the table.
Source: Adapted from van Vliet et al. (2006).

moist (Fig. 4 ; Hunt et al. 2019). This measure for mitigating N_2O is consistent with those described above for increased plant N uptake and reduced loss of NH_3.

Researchers in Washington State, USA, developed a scheduling tool called Application Risk Management (ARM) to mitigate the risk of leaching and run-off (Embertson 2016; https://agri-nmp-msa.apps.silver.devops.gov.bc.ca/). The tool can reduce the risk associated with spreading manure on grass in cool winter weather by taking account of both field conditions and near-term weather forecasts (72 h). On-farm studies showed that successful mitigation of leaching losses depends on field conditions and that, in general, ARM management reduced concentrations of soil NO_3 (Cox et al. 2018).

This concept was tested in a controlled field study in nearby coastal BC. Lower soil NO_3 concentrations were observed for dairy slurry applied in winter (February) than in autumn (November) and overall lower concentrations were observed for dairy slurry than for NH_4-NO_3 fertilizer applied at the same timing (Fig. 5, below; Hunt et al, unpublished data). These findings suggest that dairy manure can be safely applied on (unfrozen) soil in late winter to early spring to mitigate NH_3 loss while also reducing NO_3 potential leaching compared

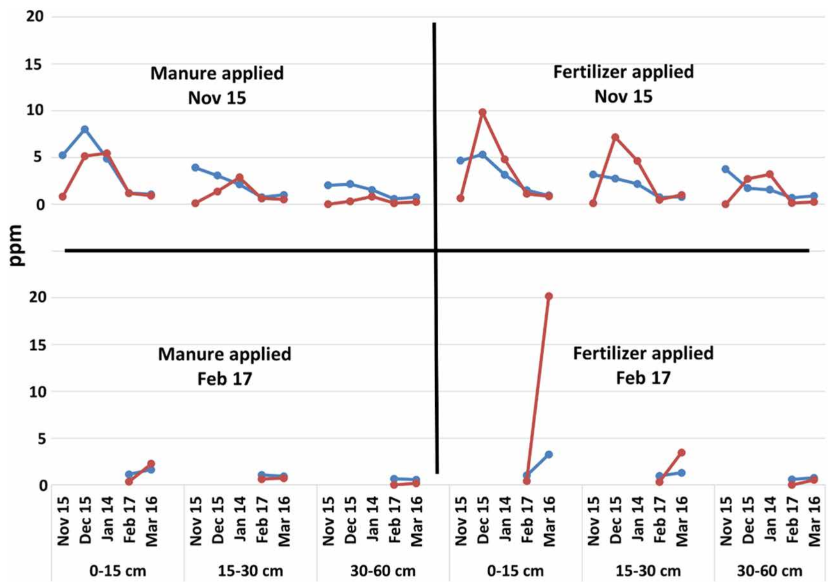

Figure 5 Soil NO_3-N (red) and NH_4-N (blue) concentration after application of dairy slurry and NH_4-NO_3 fertilizer in November (top panels) and February (bottom panels) (2014-2015) at three soils depths (0–15 cm; 15–30 cm, and 30–60 cm) under high winter rainfall conditions in south-coastal BC, Canada. The data suggests lower risk of NO_3 leaching after manure application in winter (mid-February) compared to Fall (mid-November) (unpublished data)

to autumn applications, provided that tools such as ARM are employed to reduce runoff risk. Importantly, manure and slurry application onto wet soils or in cool, rainy weather can increase the loss of P in run-off or preferential flow (Kumaragamage and Akinremi 2018). As such, the relative risks of run-off losses of N and P vs emissions of NH_3 and N_2O (see below) must be balanced when considering the timing of manure applications to soil.

The agronomic benefits of early slurry application on grass include matching the slow rate of crop N uptake in spring to the gradual microbial nitrification of NH_4 in the applied slurry. This concept is also referenced under the 'TSUM' degree-day indicator used for timing application of N fertilizer on grass in early spring (Kowalenko et al. 1989: see www.farmwest.com), but now used by farmers for timing of both fertilizer and manure application. TSUM units are accumulated growing degree days (0°C base) from January 1 until a total of 200 is reached, which in coastal BC occurs in mid-February when spreading slurry on grass is deemed to be agronomically efficient and safe on flat fields with low run-off as seen above. Early application of slurry is important to farmers with limited storage capacity. Also, frequent emptying of slurry stores will reduce CH_4 emissions (VanderZaag et al. 2013).

Indeed, applying manure during the cool non-growing season is essential for farms with limited manure storage capacity. To reduce the risk of leaching, however, regulations in many regions require that there be a well-established crop to capture nutrients from manure applied between autumn and spring. Of course, this is not possible on land used to grow maize silage unless a robust cover crop is successfully established after maize harvest, which may be difficult in years with a late maize harvest or when autumn weather is too wet, dry, or cold for successful establishment of cover crops. An alternative to autumn planting is interplanting the cover crop into the growing maize so that it is well established in the maize understory and can grow rapidly through the shoulder season, soon after the maize is harvested. One crop well suited for intercropping with maize is biennial Italian ryegrass (*Lolium multiflorum* L.), a high-protein, highly palatable cover crop that has proven over years of research and on-farm experience to tolerate shade, drought, and disease loading in the maize understory and to recover well from traffic caused by maize-harvesting equipment (Fig. 6). Seeding the Italian ryegrass when maize is at the 5–6 leaf stage maximizes establishment while minimizing competition with maize by the grass.

A well-established, actively growing cover crop can recover 40–70 kg ha^{-1} of residual soil N after maize harvest in autumn; residual soil N is almost unavoidable in manure-treated fields because maize ceases to take up N in late summer, while organic N from manure and soil continues to mineralize. The cover crop will also respond well to applications of 20–30 m^3 of slurry (100–150 kg total-N ha^{-1}) in late February and March, thereby allowing the

Figure 6 Italian ryegrass inter-seeded between rows of maize at the six-leaf stage, shown in late summer (left) and in early next spring (right). Photos by D.E Hunt, Agriculture and Agri-Food Canada.

Table 3 Fall and spring yield and N uptake of Italian ryegrass inter-seeded at 6-leaf stage of corn, Agassiz 2018–2019

Sampling stage	Sampling date	Biomass (t DM ha^{-1})	N Uptake (kg N ha^{-1})
Under maize canopy at the time of silage harvest	2-Oct-18	0.5	17
Autumn growth after maize harvest but before winter freezing conditions	19-Nov-18	1.3	39
Spring growth harvested as a grass silage crop	29-Apr-19	3.7	79

Source: Adapted from: Hunt and Bittman (unpublished data).

farmer to clear manure storage space while also promoting growth of a forage crop that can be used to complement summer maize grown on the same land. Table 3 shows some typical Italian ryegrass yield and N uptake for Agassiz, BC.

Another approach to facilitating infiltration of slurry TAN into the soil in order to reduce NH_3 emissions and improve crop N uptake involves separating slurry into liquid and solid fractions. The thinner and less viscous liquid fraction contains most of the manure TAN, which will be easily adsorbed in the soil (Table 1).

Currently, slurry separation is done on farms by mechanical filtration, such as the screwpress separator (Möller et al. 2000), to remove solids for re-use directly or after composting as a high C:N soil amendment on farms with low or declining soil OM (Zhang et al. 2019; Franzluebbers et al. 2021). It is also now used for bedding and mulch for certain high-value horticultural crops such as small fruits. Thus, separated manure solids can help remove some nutrients off-farm. The liquid fraction retained after filtration will have a lower C:N ratio but a similar P:N ratio to the original slurry because the particles containing P will pass through the filters (Möller et al. 2002). Instead, large batch-type centrifuges are required to effectively balance the N:P ratio of slurry to match crop needs; these may be particularly appropriate for farms needing to remove manure off-site and export large amounts of excessive P. In an on-farm study in coastal BC, manure separation via mobile centrifuges significantly improved the N:P ratio of the supernatant but at a significant financial and energy cost (https://www.agproud.com/articles/45270-centrifuges-an-option-for-dairy-manure-nutrient-management). Given the low commercial demand for the high-P sediment produced, there is currently little interest in this technology in Canada.

In slurry with <7% solids, natural settling of solids in tanks or ponds is a low-cost alternative to centrifugation. Table 1 shows the properties of the whole slurry compared to the supernatant (liquid fraction) after several months of storage in a two-stage lagoon joined by a weeping wall. The percent dry matter of the slurry was decreased from 5.9% (a typical value for dairy slurry) to 1.6% (a typical value for pig slurry) while the ratio of TAN:total N increased from 0.52% to 0.66% and the ratio of N:P increased from 5.2 to 9.7. The triple benefits of this liquid fraction, from a nutrient-use perspective, are (i) faster potential soil infiltration, (ii) a higher proportion of rapidly available N, and (iii) relatively less P loading. That being said, the higher pH (7.6 vs 7.0) of the liquid fraction is a potential driver for greater NH_3 emissions if soil infiltration is delayed, e.g. in soils that are saturated, hydrophobic, compacted, or crusted.

A 6-year trial using a low-emission trailing shoe to apply whole slurry or the liquid fraction (obtained from a two-stage settling lagoon) showed that plant N uptake from the slurry liquid fraction was significantly higher than from whole slurry applied at equivalent rates of total-N (Fig. 7; Bittman et al. 2011). Apparent plant N recovery was 41.6% of total-N from the liquid fraction compared to 25.5% for the whole slurry which averaged over the 6-year trial, likely included some uptake of N released from legacy organic N from previous years, especially for the organic N-rich whole slurry treatment. The higher rate of N recovery from the liquid fraction can be attributed largely to reduced NH_3 loss after application (Pedersen et al. 2021) although the effect of separation on NH_3 emissions is not always consistent (Bhandral et al. 2009) probably due to poorly understood complications at the manure–air or manure–soil interface, like surface crusting or hydrophobic soils in hot weather. Percent recovery of applied total-N was greater from mineral fertilizer (54.6%) than from the separated slurry (41.6%), but similar based on the mineral N fraction (Fig. 7).

In the same trial, much lower total P was applied in the liquid fraction than in the whole slurry treatment: at an application rate of 400 kg total-N ha^{-1} (nominal), the liquid fraction supplied about 47 kg P ha^{-1} while the whole slurry supplied about 78 kg P ha^{-1} (Bittman et al. 2011). Using data from Zhang et al. (2021), it was determined that the annual P surplus (in excess of crop uptake)

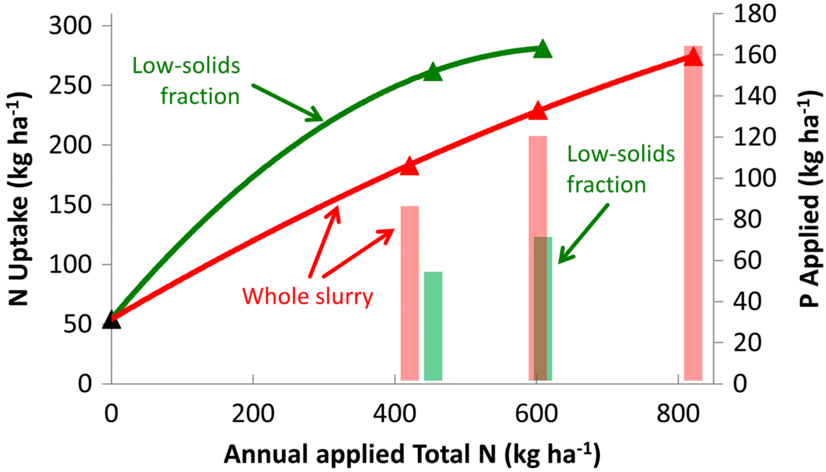

Figure 7 N uptake by tall fescue (6-year mean) receiving either whole dairy slurry (red) or the liquid fraction (green) after settling in a two-stage lagoon system. The vertical bars indicate the P loading at two application rates of whole slurry and liquid fraction. The manure properties are shown in Table 1 based on Bittman et al. (2011).

was 15.1 kg P ha^{-1} for the separated liquid fraction compared to 36.8 kg P ha^{-1} for the whole slurry treatment. After 11 years of applying separated dairy liquid, Zhang et al. (2021) reported that there was no evidence of excess P loading in soils in terms of extractable P (Kelowna extract) or total P although some P loading was evident at high rates of whole slurry. There was also little effect of legacy P (or N) from application of the liquid fraction on maize planted after the grass was terminated. With more effective settling techniques to remove greater volumes of solids, or a small addition of N fertilizer, the liquid fraction could be used for optimum yield and N uptake of grass at low cost and without the risk of applying surplus P; such an approach would represent a significant advance in manure management on intensive dairy farms. A companion study (Hunt et al. 2019) showed that the N_2O emission factor was similar for applications of whole manure and the separated liquid fraction (~0.63) and that emissions from whole manure were similar to or higher than from separated liquid manure, based on crop yield, but lower than from mineral fertilizer. This shows that manure separation did not cause N_2O pollution swapping despite the higher moisture content and likely lower NH_3 loss for the liquid fraction than whole slurry.

The strategy of separating the liquid manure fraction in order to reduce emissions and conserve N has been questioned because of limited options for effectively using the remaining solid fraction, which can give off NH_3 during storage and land application (Bittman et al. 2014a). We assessed the sludge in the bottom third of the manure tank, after decanting the thinner supernatant,

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as a replacement for commercial mineral P fertilizer for maize (Bittman et al. 2012; Hunt et al. 2016; Hunt and Bittman 2021). Extensive trials on dairy farms in coastal BC have shown that P fertilizer (mono- or diammonium phosphate) applied using a mechanical seeder in bands placed 5 cm below and to the side of the maize seed furrow, benefited early maize growth and advanced maturity by a few days even on high P soils (https://farmwest.com/resources/books/advanced-silage-maize-management-2004/chapter-3/). Two trials were conducted in which the sludge was applied at ~30 kg P ha^{-1} by injection (15 cm deep) at maize row spacing (75 cm). After 2–3 days, the maize was planted 0–15 cm off the injection furrow. The first study showed that the sludge did not impede root colonization by arbuscular mycorrhizae and that at close placement (5 cm) all yield parameters were similar for maize receiving commercial fertilizer and for maize receiving the separated thick slurry fraction (Bittman et al. 2006, 2012). In the second study, the silage maize received three sludge rates which were supplemented with commercial fertilizer to provide equivalent rates of total-N, i.e. fertilizer plus precision-placed dairy sludge (Hunt and Bittman 2021; Fig. 8). This trial showed that crop P recovery from sludge was similar to that from mineral P fertilizer at equivalent rates of total N. However, crop yields were slightly reduced in the lower N sludge treatments because these received a higher proportion of organic N from manure than from chemical fertilizer. In the moderate sludge treatment (32.5 kg P ha^{-1} and 160 kg N ha^{-1}), yield was 1.3 t ha^{-1} lower for the sludge treatment, but 22% of the total N applied was not-readily-available organic N. Apparent P recovery rate from slurry P was affected by N application and could not be fully teased out. Note that at the lower sludge and high N rate, apparent P recovery was close to 90% but yield was about 1 t ha^{-1} lower than the high sludge rate at equivalent total N (more mineral N). The injected slurry at 32.5 kg P ha^{-1} fully supplied the early (not shown) and season-long P requirements of maize, obviating the need for mineral fertilizer. Successful use of precision-placed (whole) dairy slurry for starter P has been reported in Germany, where this practice is now used commercially (Federolf et al. 2015), in Denmark (Pedersen et al. 2020) and The Netherlands (Schröeder et al. 2015), Note that injection of sludge substantially increased N_2O emissions compared to broadcasting, a tradeoff that was substantially addressed by mixing the nitrification inhibitor dicyandiamide into the sludge before application (Hunt and Bittman unpublished).

When assessing plant uptake of manure N, it is important to consider the influence of the crop species. We compared uptake of N from slurry and commercial fertilizer by three perennial grasses: orchardgrass (*Dactylis glomerata*), tall fescue, and perennial ryegrass (*Lolium perenne*) from 2004 to 2010 on soils pre-treated with manure since 1996 (Table 4) (Bittman et al. 2014b). Percent N uptake across grass species averaged over the 7 years was greater for fertilizer than for slurry N (72.3% vs 65.1%, respectively) at an N application rate

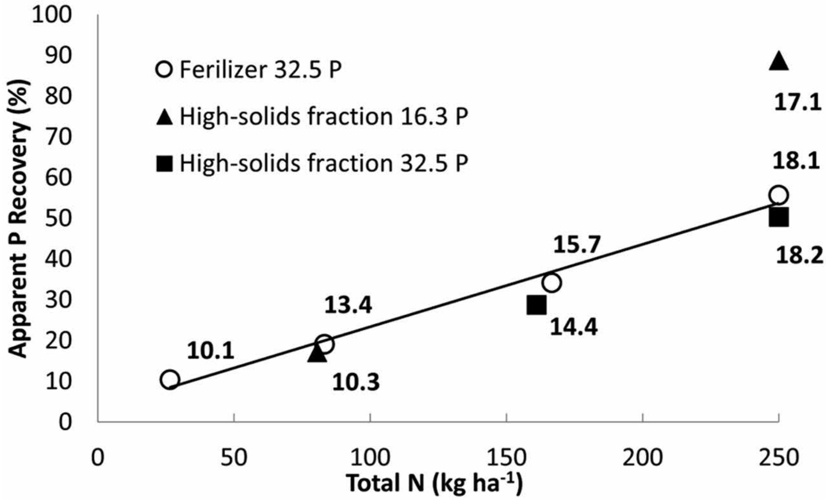

Figure 8 Apparent P recovery (%) by silage corn (recovery relative to applied P adjusted for control) treated with precision-injected (<10 cm from corn row) separated dairy slurry (high solids fraction); the slurry fraction was applied at 16.3 (triangles) and 32.5 (squares) kg P ha^{-1}. Total N applied in the high-solids fraction was 80.5 kg ha^{-1} and 161 kg ha^{-1} at the low and high P application rates, the remaining N coming from commercial fertilizer (total applied N on X-axis). Response to mineral N fertilizer rates with 32.5 kg P ha^{-1} is depicted by the open circles and the regression line. P recovery is shown at equivalent total N rates. The data show that manure and fertilizer P recovery are similar at equivalent total N rates. The values associated with each dot represent yield (t DM ha^{-1}) which is somewhat lower with slurry than mineral fertilizer due to less available N in slurry, but improved with increasing fertilizer N; at high addition of mineral N (250 kg N ha^{-1}), corn yield is equivalent from manure and fertilizer (~18.1 t DM ha^{-11}) showing similar efficacy of manure and fertilizer P. Note, at low manure and high total N rates, P recovery >90% but yield is slightly depressed likely by insufficient manure P. (Data is mean of 3 years; based on Hunt and Bittman 2021).

of 400 kg total-N ha^{-1} (nominal). The average N uptake, across all N treatments, was consistently lowest for perennial ryegrass, due to lower total yield potential and, possibly, shallower roots, less drought tolerance in summer, and less winter hardiness. In general, orchardgrass responded better to commercial fertilizer while tall fescue responded better to (whole) slurry, especially during vigorous spring growth. We attribute this to more consistent season-long growth for tall fescue than orchardgrass, which better matches nutrient availability from slurry than from mineral fertilizer. In the first-cut (taken in mid-May), tall fescue took up more N (16–37 kg ha^{-1}) from slurry than orchardgrass, perhaps due to more vigorous spring growth or relative preference for NH_4, but annual differences in N uptake were somewhat smaller. Crops appear to differ in their preference for NH_4 and NO_3 but this requires more study. The uptake of slurry N by tall fescue also generally increased over the 7 trial years, perhaps due to legacy N and the excellent hardiness of tall fescue.

Table 4 Annual N uptake by three forage grasses (2004-2010) treated with dairy slurry, fertilizer, or both dairy slurry + fertilizer at contrasting total N rates (shown)

Treatment		N Rate	Orchardgrass		Tall fescue		Perennial ryegrass		Mean	NUE[b]
		kg ha^{-1} year^{-1}								
Control		0	100	J[a]	94	J	77	K	90	
Fertilizer	Low	200	239	G	210	H	178	I	209	104.5
Fertilizer	**High**	**400**	**310**	**D**	**289**	**E**	**268**	**F**	**289**	**72.3**
Slurry	**Low**	**384**	**263**	**F**	**268**	**F**	**219**	**H**	**250**	**65.1**
Slurry	High	724	332	B	371	A	294	E	332	45.9
Fert+slurry	High	546	371	A	374	A	321	C	355	65.0
Mean			269		267		226			

[a]Values not followed by same letter are significantly different at $P < 0.05$.
[b]NUE is nitrogen use efficiency, N uptake/N applied as a percent. Values greater than 100% can be due to atmospheric N deposition, biological N fixation and net soil N mineralization. Bolded rows received similar rates of total N.Alt
Source: Adapted from: Bittman et al. (2023).

There are a few other studies on the relative response among species to fertilizer and manure. In a New York State study, where semi-solid manure (14–19% DM) was applied by broadcasting, orchardgrass had lower yield but higher tissue N concentrations than tall fescue (Cherney et al. 2002). To optimize the efficiency of slurry N uptake by grass, it is important to appreciate specific crop nuances such as seasonal and total growth and preference or tolerance for N species, especially in high-input systems where over-application will not only reduce NUE but inevitably lead to environmental losses (see effects of long-term manure applications, below).

5 Assessing long-term manure and slurry application

Interpreting crop nutrient uptake and NUE of manure from short-term trials can be problematic. As a result of pre-trial soil disturbances, changes in the cropping system, trial establishment activities, etc., soil nutrient dynamics are perturbed and not in steady state. Hence, estimates of crop N uptake require adjustments for net soil N mineralization, which is often done by subtracting available soil N concentrations and crop N uptake on untreated control treatments (i.e. 'apparent N uptake'). This approach provides only an approximation of the available N in the absence of manure application, since it does not include the effects of N priming on mineralization in the treated soil. Also, crop N uptake includes both manure-derived readily available N (in the form of TAN) plus N that is gradually released from the organic fraction in the manure (about 40-50% of the total slurry N; Table 1). Organic N mineralization is controlled by soil conditions, especially temperature and moisture, and other factors such as soil pH and aeration. Net mineralization of the manure organic fraction is also influenced strongly by the C:N ratio of the manure which, in turn, is affected by percent crude protein and fiber in the cattle diet and the amount and type of bedding used (Webb et al. 2013). In the cool soils of Denmark, the release of organic N from applied dairy slurry, in the 5 years after application, followed a decay curve of 17%, 17%, 8.5%, 4%, and 4% (Sørenson et al. 2017). In the milder climate of the Netherlands, these values were slightly higher in years 1 and 2 (21%) but similar thereafter. Over the 5-year study period, mineralization of organic N in cattle slurry was 51% compared to 71% for pig slurry.

Contrary to short-term agronomic trials, which are inevitably affected by rarely reported pre-trial conditions, long-term trials allow soil to reach a quasi steady state and more fully account for the mineralization of organic N derived from repeated applications of manure. Long-term trials also allow for monitoring of changes in SOC and in other soil minerals, like P and Cu. We evaluated the efficacy of N from dairy slurry relative to commercial fertilizer (and slurry + fertilizer) for tall fescue, between 1996 and 2002 at Agassiz, BC (Bittman et al. 2007). The slurry from commercial dairy farms was applied uniformly to replicated plots with low-emission trailing shoes at 19-cm spacing. Both slurry and fertilizer were applied in four equal doses each year: twice in cool weather (March and September) and twice in warm weather (June and August) to supply each of four grass harvests. The manure was applied at target (nominal) annual rates of 400 kg total-N ha^{-1} and 800 kg total-N ha^{-1} or 200 kg ha^{-1} and 400 kg ha^{-1} of TAN (actual rates in Table 5). The N fertilizer (NH_4-NO_3^- 'Fert' in Table 5) was broadcast at 200 kg N ha^{-1} and 400 kg N ha^{-1} with other nutrients (and lime) supplemented according to soil test requirements. The experiment also included a treatment where applications of fertilizer at 100 kg

Table 5 Fate of N from dairy slurry and mineral fertilizer (Fert; NH_4-NO_3) applied to tall fescue 1996–2002 at Agassiz, BC

Treatment	Annual min/total N (nominal) Kg ha^{-1}	Apparent N recovery	Stored soil N	Unaccounted N
		% of applied total-N		
Control	0	–	–	–
Fert-low	200/200	67.1	22.4	10.5
Fert-high	400/400	58.7	14.3	27.0
Slurry-low	200/400	42.0	32.0	26.0
Slurry-high	400/800	37.4	30.2	32.4
Alternate-high[a]	400/600	53.3	23.1	23.6

[a]Alternating applications of Fert-high and Slurry-high.
Note: Stored soil N was measured by soil sampling and nitrogen analysis.
Source: Adapted from: Bittman et al. (2007).

N ha^{-1} were alternated with manure at 200 kg total-N ha^{-1} each application (annual total-N = 600 kg N ha^{-1}) and an unfertilized control. Over 7 years, about 60–67% of applied N was recovered from the Fert treatment, about 37–42% was recovered from slurry, and 53% was recovered from the alternate treatment with relatively lower N recoveries observed at the higher N application rates (Bittman et al. 2007) as reported by Webb et al. (2013).

These recovery rates were lower than expected based on concentrations of available TAN in the slurry; the fertilizer equivalency of the slurry at a comparable total N application (400 kg N ha^{-1} nominal) was 70% based on 42% recovery of slurry N vs 60% recovery of fertilizer N. Over 7 years, 14% of fertilizer N and 32% of slurry-applied total-N accumulated in the soil (Table 5). Nitrogen loss calculated from cumulative uptake plus cumulative soil storage vs N applied was lowest for the low fertilizer treatment but similar for the fertilizer and slurry treatments applied at the 400 kg N ha^{-1} nominal rate, due to lower uptake but greater soil storage for slurry (Table 5). It was deduced from this multi-year study that NH_4-NO_3 fertilizer, which emits <5% fertilizer N as NH_4 (Van der Weerden and Jarvis 1997), lost N mainly by leaching over the non-growing season (Kowalenko 1989) and that slurry N was lost by NH_3 emissions soon after application, especially in summer (as predicted by the ALFAM and ALFAM 2 models; Søgaard et al. 2002; Hafner et al. 2019) and by leaching and denitrification

Direct measurement of the suite of N losses over multiple years and variable weather conditions is difficult to implement because they are laborious and requires an assortment of specialized equipment. Also, losses can be missed when they occur near detection limits over long periods or as sudden bursts (e.g. following freeze-thaw events; Fig. 9), which are easily missed (Pelster et al. 2022; Hunt et al. 2019). In this way, N loss pathways inferred from long-term trials may be less precise but more robust than direct measurements.

Longer-term-treatment effects of this trial were re-examined after 15 years (Zhang et al. 2021). Mean annual yields for fertilizer- or slurry-treated grass ranged between 11.4 Mg dry matter ha^{-1} and 15.0 Mg dry matter ha^{-1}, while total N uptake over the entire trial duration ranged from 1530 kg N ha^{-1} (102 kg N ha^{-1} $year^{-1}$) for the control to 5565 kg N ha^{-1} (371 kg N ha^{-1} $year^{-1}$) for the alternating (Alt-high) treatment (Table 6). Overall, actual NUE (unadjusted for unfertilized plots) varied between 114.1% (Fert-low) and 48.6% (Slurry-high). At 400 kg total-N ha^{-1} (nominal) application rate, the NUE of the Slurry-low was similar to commercial fertilizer (Fert-high) at 77.6% and 74.5%, respectively. The high values for slurry can be attributed to the low emission slurry application and capture of mineralized legacy organic slurry N. High crop yields may also play a role. Notably, the Alt-high treatment had the highest yield and crop N recovery but a lower NUE (67.6%).

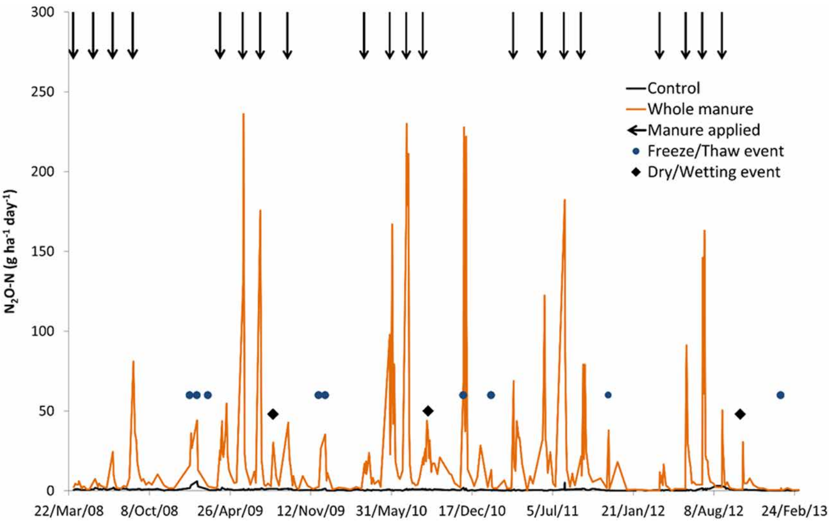

Figure 9 Daily nitrous oxide (N_2O-N) emissions measured between 10 April 2008 and 6 March 2013 (~59 months) on replicated perennial grass plots treated with dairy slurry (nominal 600 kg N ha^{-1} year^{-1}) in four equal doses. Day of manure application, freeze/thaw events and dry/wet cycles are depicted by arrows, circles, and diamonds, respectively. Source: Adapted from: Based on Hunt et al. (2019).

In contrast to the earlier study (Bittman et al. 2007), only 13–15% of the applied slurry N was stored in the soil compared with −1.9% and 8% of the low and high fertilizer N, respectively (Zhang et al. 2021; Table 6). The lower percentage of soil N storage after 15 years than after 7 years suggests that, over time, soil N pools move towards an equilibrium in which N mineralization rates approach N immobilization rates. The Alt-high treatment sequestered less N than the Slurry-low treatment (3.2% vs 13% of applied N, respectively) even though both treatments received the same amount of slurry N and produced similar amounts of biomass (14–15 Mg dry matter ha^{-1} year^{-1}). This unexpected result suggests that the added mineral N in the Alt-high treatment increased N mineralization rates (lower C:N ratio in soil), while possibly increasing the shoot to root ratio of the grass (i.e. lower inputs of root biomass N).

Nitrogen losses ranging from 36.2% to −12.2% (based on unadjusted NUE values) are probably underestimates because wet and dry atmospheric deposition of reduced and oxidized N species is not usually measured and may be as high as 30 kg N ha^{-1} year^{-1} where there is intensive livestock production (Hao et al. 2009; Table 6). The adjusted NUE, which subtracts the N uptake in unfertilized Control plots, corrects for N deposition but is likely an over-adjustment, due to higher biological N fixation in the Control plots than treated plots due to more volunteer white clover (10–15% ground cover in Controls compared to <5% in treated plots, unpublished data). Furthermore,

Table 6 Responses to applications of mineral fertilizer (NH_4-NO_3) and dairy slurry on grass over a 15-year period: annual yield and N uptake by forage (total of four cuts per year); un-adjusted nitrogen use efficiency (NUE); adjusted NUE, total-N sequestered in soil over 15-year period (measured); changes in natural abundance δ15N in herbage. Un-adjusted NUE is defined as (total-N uptake by herbage)/(total-N applied); adjusted NUE is defined as ((total N uptake by treated herbage) − (total N uptake by control herbage))/(total-N applied)

	Applied Total-N kg ha^{-1}		DM yield t ha^{-1}	Uptake tot-Nkg ha^{-1}	NUE %Unadjust.	NUE %Adjust.	Sequest. N% of applied	lost N% of applied	Herbage δ15N (‰)	
Treatment	Annual	15 year	Annual	15 year	15 year	15 year	15 year	15 year	1996	2010
Control	0	0	5.89	1530	–	–	0	–	4.32	2.01
Fert-low	198	2970	11.36	3390	114.1	93.9	-1.9	-12.2	3.62	1.10
Fert-high	392	5880	11.11	4380	74.5	64.3	8.2	17.3	3.09	0.77
Slurry-low	379	5685	13.89	4410	77.6	67	13	19.4	5.99	5.20
Slurry-high	726	10890	14.34	5295	48.6	43.1	15.2	36.2	6.39	7.40
Alt[a]-high	549	8235	14.96	5565	67.6	60.3	3.2	29.2	4.72	4.27

[a]Alternating applications of Fert-high and Slurry-high.
Source: Adapted from: Zhang et al. (2021).

micro-run-off may also transfer some N to low N plots and dry deposition of NH_3 may be greater on control plots due to steeper atmosphere–plant N gradients (Sutton et al. 1993). Thus, it is likely that the true NUE falls somewhere between the adjusted and unadjusted values but closer to the unadjusted values.

Determination of natural abundance $\delta^{15}N$ values of crop tissue can be used to make inferences about the source of N taken up by the plant. This is because fertilizer $\delta^{15}N$ value tends to be lower than that of manure, while urine $\delta^{15}N$ value tends to be lower than that of faeces. Even in the first year of the trial, differences in the sources of N inputs were reflected in the natural abundance $\delta^{15}N$ values of the harvested herbage and became more marked over time (Table 6; Zhang et al. 2021). For example, herbage $\delta^{15}N$ values in Fert-treated plots, especially at the high rate, declined towards fertilizer $\delta^{15}N$ value, particularly after ~10 years, showing that most of the N taken up by the crop in Fert plots was derived directly from fertilizer (not shown). By contrast, the herbage $\delta^{15}N$ values in the Slurry-low and Alt-high treatments remained largely unchanged through time, suggesting that the experimental field had received similar forms of N inputs prior to the trial (which was supported by the oral history for that field). The herbage $\delta^{15}N$ values in the Slurry-low and Alt-high plots were much lower than that of applied slurry (~11.9‰), reflecting preferential root uptake of urine N, which is more depleted in ^{15}N than faeces. Thus, the higher herbage $\delta^{15}N$ values in the Slurry-high treatments suggest that a greater proportion of N uptake came from faeces. Finally, the herbage $\delta^{15}N$ value in the control treatment (~2.01‰) probably reflects the uptake of N derived from biological N fixation and/or atmospheric deposition (Zhang et al. 2021).

In long-term dairy slurry trials conducted in northern Quebec, N accumulation in high clay soil was attributed to manure applied to forages grown in a rotation with cereal crops and soil storage of dairy slurry-derived N applied to arable crops was found to be limited (D'Amours et al. 2021). Canada-wide, low-soil C storage (5%) from dairy slurry compared to solid cattle manure, in mainly arable crops, likely reflects a low C:N ratio (Liang et al. 2021), which is consistent with higher C storage observed from dairy manure than from chemical fertilizer (Maillard et al. 2015, 2016).

Indeed, as mentioned above, the current interest in increasing SOC as a means of supporting climate change mitigation and improving soil health has renewed interest in the use of manure as a C-rich soil amendment. Numerous studies and meta-analyses have shown the potential for increased SOC with applications of solid manure (Gross and Glaser 2021; Li et al. 2021b), but research on the effects of manure slurry on SOC storage remains relatively scant (Maillard et al. 2014; Bolinder et al. 2020). Nevertheless, several Canadian studies have explored the longer-term impact of continuous slurry applications on SOC stocks and soil health. In the long-term trials described directly above, the SOC stock of the Slurry-high treatment (16.1 kg C m^{-2}) was significantly greater than the Control and Fert (13.2–13.7 kg C m^{-2}) treatments after 17 years, while the SOC stock of the Slurry-low treatment was intermediate (14.6 kg C m^{-2}; Maillard et al. 2015). This positive effect of high slurry application on SOC stock was attributed both to inputs of solid material in the manure (derived from undigested forage and wood chips used as bedding material) and to increased crop growth (which tended to be higher in the Slurry-high treatments than in the Slurry-low or Fert treatments) but note that the above-ground biomass was mostly harvested and removed. The increased SOC was concentrated in the top 20 cm of the soil; although there was limited mixing of the SOC into deeper soils, where it might be protected from decay, greater formation of C-rich organo-mineral complexes near the soil surface suggested that this newly formed SOC may be fairly stable. Similarly, a 21-year study comparing the effects of liquid dairy manure and fertilizer N applications on SOC stocks in combination with a cereal monoculture or cereal-perennial forage rotation found that applications of dairy manure increased SOC stocks in the cereal-perennial forage rotation treatment; again, treatment differences were concentrated in the top 20 cm of soil (Maillard et al. 2016). The authors proposed that SOC stocks were only observed in the forage rotation treatment because of reduced tillage frequency, and the addition of high-quality residue derived from red clover (*Trifolium pretense* L.). Together, these studies show that both direct inputs of manure-derived organic C and plant biomass growth following manure applications mediate the response of SOC stocks to applications of dairy manure. Further work is required to explore the 'stability' of dairy slurry-derived SOC.

Important questions also remain on how applications of dairy manure influence the composition and function of the soil biotic community. In a perennial grass sward dairy manure, whole or separated liquid fraction, applied at 400 kg total N ha^{-1} increased soil microbial biomass, microbial activity, and soil health enzyme indicators over control and mineral fertilizer, with no difference between the form of manure (Neufeld et al. 2017). However, the ratio of fungi:bacteria was significantly higher following applications of whole manure than after applications of the manure separated liquid fraction or commercial fertilizer, suggesting that organic C-rich manure can alter the structure of the soil microbial community with possible implications for soil C accumulation. In a separate trial, bacterial counts showed a rapid response to applications of whole dairy slurry compared to fertilizer, suggesting that soil bacteria may be capable of rapidly immobilizing manure N (Bittman et al. 2005). Microbivorous protozoa, bacterivorous nematodes, and fungivorous nematodes were also more abundant in soil treated with manure than in control or fertilized soil, indicating an enhanced microbial food web which may explain the relative lack of differences in microbial community size among treatments (Bittman et al. 2005; Forge et al. 2005b). Microbial processing of

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SOC contributes to the formation of C-rich organo-mineral complexes that are more resistant to decay (Lehmann and Kleber 2019), but the relationship between fungal (or bacterial) community composition and the formation of more stable forms of SOC remains an open question (Cotrufo et al. 2019). The response of the soil fungal community to applications of dairy manure may be mediated by available N and P (Ma et al. 2016), so applications of manure with different C:N and C:P ratios may elicit different pathways of SOC formation with varying resistance to mineralization.

Of note, the dairy slurry increased populations of the parasitic nematode, *Pratylenchus penetrans*, which contrast with some previous studies showing reductions but may be related to lower doses (Forge et al. 2005a). Slurry manure increased the population of a single species of carabid beetles (*Pterostichus melanarius*) which consumed more onion maggot (*Delia antiqua*), but decreased indicators of carabid diversity (Raworth et al. 2004).

6 Dairy manure and farm management

Over the long term, we estimate a NUE of 70% for slurry applied with a low-emission trailing shoe applicator on a high-producing grass in a seasonally moist climate. The NUE could be further improved, e.g. with shallow injection (Webb et al. 2010) or other methods that facilitate slurry-N infiltration and stabilize NH_3 (separation, rolling tines, acidification). Our estimate of NUE is higher than national efficiency values in the EU, which are mostly under 60% (reviewed by Webb et al. 2013). Across farms and crops, there will be a range of NUEs, depending on soil attributes, weather conditions, and the ability of farmers to manage their crop productivity (variety selection, pest control, irrigation) and soil productivity (compaction and conservation of soil C) and even to set manure/fertilizer rates (which requires some degree of guessing and intuition by farmers to anticipate weather and revenue).

There are soil testing and decision-support tools intended to help farmers improve their crop and nutrient management practices. A fairly recent innovation is real-time N modelling tools such as ADAPT-N® that can improve NUE (in maize) by guiding in-season adjustments of fertilizer rates and timing (van Es et al. 2023), although at present most tools have not been calibrated for N from manure. Advances in visual modelling platforms, like STELLA/ ITHINK©, are being developed to customize N models for a larger array of soils, crops, and nutrient inputs, including manure (e.g. Dion et al. 2020; Dorais et al. 2019; Hirsch 2007).

Because there are large differences in management skills and farm challenges among farmers, on-farm efficiencies across the sector can be gained by training, education, and mentorship programs. Living Labs have been implemented across Canada, some on dairies in BC and Quebec, to help farmers identify and adopt best management practices, such as in-crop testing, variable nutrient rates, cover cropping, efficient manure use, and nutrient budgeting. The objectives of these initiatives are to help mitigate climate effects and reduce other possible negative environmental impacts associated with milk production while maintaining farm production and profits (Longchamps et al. 2023).

To ensure efficient use of N inputs on a dairy farm, N losses from slurry must be staunched from barns and manure storages, and from grazing animals that have low NH_3 emission losses but, paradoxically, poor nutrient distribution which leads to inefficiencies (Webb et al. 2013). Increased adoption of measures, such as manure storage covers and manure acidification can reduce air pollution and preserve manure N (Sutton et al. 2022). However, these measures may not be sufficient for farms that have limited land to produce feed and accommodate manure nutrients. For all dairy farms, particularly those with a limited land base, it is necessary to address nutrient leakages throughout their operation while also balancing farm nutrients by matching inputs and outputs, as depicted in the 'leaky pipe' in Fig. 10. The leaks in this pipe, which apply to both N and P although only N is shown in Fig.10, occur throughout the farm: from wasted feed to inefficient handling and utilization of animal wastes and to crop harvesting and storage. Whole-farm models, such as the Integrated Farm System Model, can be used to simulate nutrient flows and test different management scenarios on dairy farms (e.g. changes in fertilizer or feed, or response to climate change; Rotz et al. 2021). These approaches must also account for spatial pollution swapping; e.g.,production of imported feeds also comes with an environmental cost that occurs elsewhere, infrequently represented in whole farm models, though it is likely to be included in life cycle analyses.

The counterintuitive environmental benefits of growing maize on dairy farms was first reported on the DeMarke model dairy farm, where researchers demonstrated that replacing some grass with maize helped reduce farm N surplus

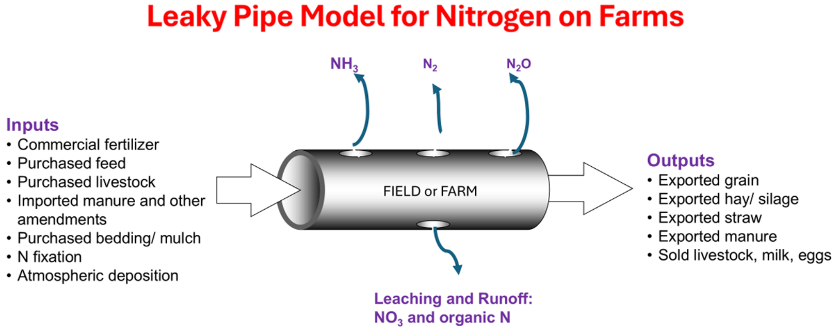

Figure 10 The leaky pipe model of N budgets for field or farm systems. Nitrogen surplus will result in leaks that can be shifted between pathways (e.g. NH_3 to NO_3) but not staunched unless surpluses are reduced.

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and NO_3 leaching, and coincidentally, irrigation water consumption (Aarts et al. 2000). Reducing N surplus does not guarantee environmental protection since there can still be poor practices in sensitive areas, but improved environmental sustainability cannot be attained without constraining surplus nutrients at the field, farm, regional, and national levels. Nutrient surpluses on farms can be mitigated by reducing nutrient imports through increasing on-farm production, reducing livestock numbers, and/or adding land; increasing export of products, including wastes or feed, can also be used to balance whole farm-nutrient budgets. Commercial pilot dairy farms, perhaps the forerunners of the Living Lab concept, have been used to encourage participatory farm management as a means of reducing the environmental impacts of dairy production (Oenema et al. 2011). As well, 'dairy farmlet' trials have been employed in New Zealand to assess the effect of changing farm practices, e.g. grazing management, on GHG emissions (Van der Weerden et al. 2018).

A research framework was initiated at the Agassiz Research and Development Centre in 2017 to help integrate nutrient and crop management at the field and farm levels. This framework, called 'semi-virtual farmlets', is intended to provide a more complete and integrated assessment of advancing farm nutrient sustainability; the framework combines (i) field testing of best management practices for nutrient use and crop production; (ii) crop and soil sampling and analysis; and (iii) cow nutrition models (Li 2019; Li et al. 2021a). Slurry management measures for reducing nutrient losses are tested in the field while crop management measures are integrated into the design to help improve NUE and reduce losses. Manure management measures involving manure separation and precision application are combined with improved cropping measures, such as double cropping and relaxed harvesting to produce more crop with less inputs (Fig. 11). The crops are harvested and tested for key nutritional quality factors pertinent to dairy cattle. In this hybrid approach, the on-farm feed produced, rather than actually feeding to animals, are balanced to meet cattle requirements with minimum supplemental feed importation using the feeding model: Cornell Net Carbohydrate and Protein System feeding model (4 AMTS, Agricultural Modeling and Training Systems LLC, Groton, NY) (Fig. 12; Koenig et al. 2023). This ongoing 'dairy farmlet' trial has demonstrated the potential for reduced N losses and elimination of P fertilizer. Farm feed production was improved by optimizing maize and grass allocation, and improving the nutritional balance of feed, thereby reducing the need to purchase feed supplements, lowering N excretion rates, and freeing up land to grow additional needed crops that could further replace imports. With this framework, the potential for pollution swapping has been identified, and measures have been adopted to mitigate these unintended consequences.

The progressive nutrient and crop measures integrated within these semi-virtual farmlet trials are intended to mitigate nutrient leakages and identify and

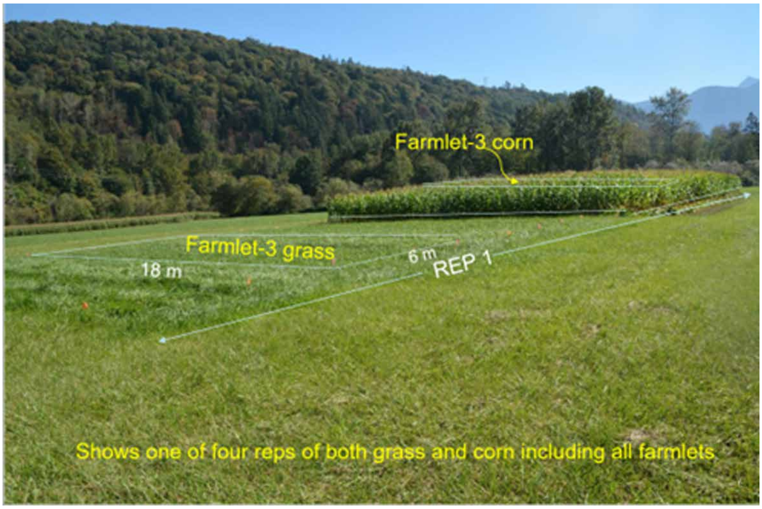

Figure 11 Field portion of 'semi-virtual farmlet' trial showing Replicate 1 with corn and grass management plots. Farmlet 3 is identified. Photo by S. Bittman and D.E Hunt, Agriculture and Agri-Food Canada.

address within the farming system any unintended negative consequences of adopting new practices. These efforts demonstrate that the sustainability of maize and grass production on dairy farms can be improved individually and in concert by sharing and optimizing resources, including land allocation for crops having complimentary and contrasting attributes in terms of plant physiology, nutrient requirements, seasonality, yield and feed quality, and different environmental risks.

7 Future trends in manure management

While there has been incremental progress on farm nutrient management, increasing societal pressures are driving more ambitious approaches to manure nutrient use. These pressures include concerns about animal production, including dairy, for its disproportionate environmental impact within the agri-food sector; the expectation that agriculture will contribute to climate mitigation; and an emerging understanding that nutrient accumulation across landscapes, especially in urban and peri-urban areas, must be rationalized (Bittman and Hunt 2024). Food production activities near cities help preserve greenspace and farmland; these farms support local food supply and safeguard food security, but it cannot be overlooked that these regions are becoming termini for farm-food nutrient streams and no strategy has been devised in Canada to return nutrients to remote feed sources. This question has been articulated in the USA as Manuresheds, an attempt to visualize the flow of feed, food, and waste nutrients

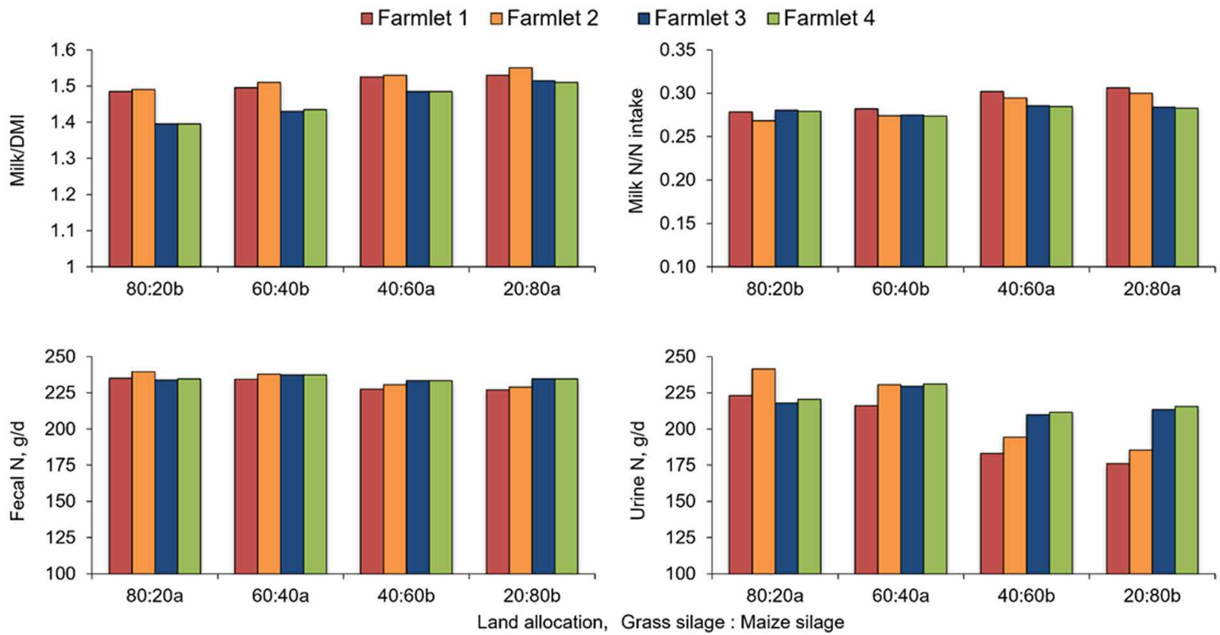

Figure 12 Effect of soil and crop measures and ratio of land allocation (grass silage:maize silage) on some production indicators determined in a 'semi-virtual' dairy system study, The study combines field experiments (Fig. 11) and simulated animal production using the Cornell Net Carbohydrate and Protein System model in an integrated assessment of farm management practices. Farmlet 1 reflects local farming practices, while Farmlets 2-4 employ improved soil/nutrient measures, improved nutrient and crop practices, and advanced measures, respectively. The indicators shown are milk per dry matter intake, milk N per N intake (= milk NUE), and excretion of faecal and urine N. The study shows that milk production and N use efficiency can be significantly improved while reducing urine N. Crop ratios (across farmlets) not followed by the same letter are significantly different at $P < 0.05$. Source: Adapted from: Koenig et al. (2023).

across land, landscapes, and geographies (Kleinman et al. 2022). In peri-urban areas and regions with large animal production, soils are likely to be replete with N, and even more so with P and other non-volatile nutrients. At best, this nutrient accumulation reflects a wasted non-renewable resource but, at worst, it is a legacy problem for future farmers and citizens. At present, processing manure to produce marketable products is expensive – in part because it requires removal of large amounts of water from manure (e.g. via filtration, centrifugation, reverse osmosis) or manure nutrients from water (e.g. NH_3 stripping).

Historically, manure has been used across the world to produce energy, mostly via direct combustion of cattle dung. Increased commitments to climate mitigation are now driving industrial-scale biogas production, especially from dairy slurries with economic supports for energy bio-CH_4 production and environmental CH_4 mitigation. More recently, tropospheric CH_4 release has been blamed for ozone pollution. In some countries and jurisdictions, biogas is limited by supplies of feedstock; to fill these gaps, crops such as silage maize may be grown, though this practice may have unintended consequences for the environment and for food security. Co-digestion of dairy slurry with maize silage may improve biogas yield, but the use of organic wastes must be carefully controlled so that digestate residues can be safely returned to the food production stream. Companies may be reticent to use unregulated waste materials, such as household wastes or biosolids, as feedstock or may relegate digestate to non-agricultural uses, such as forestry or production of dedicated biomass crops, such as switchgrass (*Panicum virgatum*) or *Miscanthus*. Reusing manure for non-agricultural uses may be justified at the larger scale, but it does not respect the circularity of nutrients, i.e. farm-to-fork-to-farm. Energy production will be in direct conflict with food production if agricultural land is used to produce energy crops rather than feed crops. Feeding crop wastes to biodigesters rather than to cattle and other livestock comes with similar philosophical problems. Furthermore, family-run dairy farms may be too small to run biodigesters effectively and economically (VanderZaag et al. 2023); they must be near other farms to capture sufficient feedstock, although artificial intelligence may help to operate small digestors, much as robotics and GPS have helped improve the efficiency of other family farm operations.

8 Conclusion

Using manure on crop land is a long-established practice and is of great value when there is limited access to mineral N and P fertilizers. It remains important across all farms to use manure to reduce mineral fertilizer inputs and improve soils; direct application of manure to soils remains the simplest and best way of using this troublesome resource. Manure is bulky and heavy, irregular and inconsistent, with an inconvenient nutrient composition that does not match crop needs.

Manure nutrients are also prone to losses as gases, solutes, and suspensions, and manure is a source of pathogens. Solving the manure conundrum so that it contributes value to farms, rather than merely posing a disposal issue is an incremental process with synergies, trade-offs, paradoxes and, often, costs. Integrated approaches for using manure are needed to fully exploit this resource, which is needed to help Canadian dairy farms reach their goal of 'net zero C'.

Dairy manure can be used to replace mineral fertilizers and thereby diminish C footprints. Manure C, properly harnessed, sequesters C in soils and, since much of the SOC stored in soils following manure application is derived from primary production (i.e. crop photosynthesis), this additional stored C may cancel some of the unavoidable C inputs on dairy farms. There are now new and better ways to use the C in dairy manure to produce cattle bedding, mulches, soil amendments, and even as substrates for energy production, especially biomethane, while reusing nutrients.

Feed self-sufficiency and land conservation are important, and inter-related, aspirations because they lead to better cropping and feeding practices which, in turn, improve the production efficiency of dairy crops, animals, and farms. With the staggering complexity and demands of modern dairy farming, it is difficult for farmers to unravel the manure conundrum. This will require a community effort, where resources, knowledge, and expertise can be shared and advanced. A model for such an effort might be the 'Collective systems with centralized feed and manure management systems' in Japan, as described by Toda et al. (2020) where several farms share a centralized feed and manure management system. In these shared systems, manure handling and crop production is managed by specialized companies, enabling the dairy farmers to focus on animal management, feeding, and milking.

Worldwide, farmers are working to solve the manure conundrum on dairy farms in the context of their diverse production systems (Ghourley and Misselbrook; book chapter in review).

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