Transdisciplinary Soil Science Research: Impacts of Dairy Nutrition on Manure Chemistry and the Environment

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In many regions of the world, the current trend of consolidation and intensification of animal agriculture often requires a greater dependence on purchased feed. As more animals are added to a fixed land base, and more feed is imported onto a farm, the excretion of manure nutrients can surpass the recycling capacity of local land, air, and water resources. In response to these environmental challenges, many industrialized countries have enacted legislation to control manure management and the emission of hazardous gasses from animal production systems. Research and extension agencies were allocated considerable public funding to develop and extend technologies that would assist livestock producers in meeting environmental standards. In response to dairy industry needs for practices that would facilitate manure management and compliance to water and air quality standards, transdisciplinary dairy nutrition-soil science research was initiated to evaluate relationships among the type and amount of P and crude protein (CP) in lactating cow rations, and milk production, manure chemistry, and environmental outcomes. Nutrient source-sink relationships provided the functional framework for this transdisciplinary research: dairy nutrition research was conducted to evaluate impacts of ration components (sources) on milk production (sink) and manure components (sinks), and soil science research was conducted to evaluate impacts of manure components (sources) on water (sink) and air (sink) quality. For example, unnecessary mineral P in supplements in dairy rations was found to be excreted entirely as water soluble P in manure and, after manure land application, increased soil test phosphorus (STP) levels, P loss in runoff, and the cropland area requirements in order for producers to comply to comprehensive nutrient management plans (CNMPs). Likewise, feeding CP above recommended levels increased the excretion of urea N in urine and subsequent ammonia (NH_3) loss from soil after manure application. The type of forage fed to dairy cows and the tannin content of dairy cow rations also impact NH_3 emission, soil N cycles, crop yield, and N uptake. Four main ingredients to transdisciplinary dairy nutrition–soil science research have been (i) an immediate and clear need for the information, (ii) the required expertise of both dairy nutrition and soil science to provide this information, (iii) the ability and willingness of scientists and other stakeholders to work together, and (iv) adequate funding.

Abbreviations: CNMP; comprehensive nutrient management plan; CP, crude protein; DMI, dry matter intake; NIFA, National Institute for Food and Agriculture; STP, soil test phosphorus.

OVERVIEW OF THE TRANSDISCIPLINARY RESEARCH NEED

Over the past half-century in the industrialized countries of the world, fertilizers and feeds have been relatively inexpensive, widely available, and used in the pursuit of maximum economic yields. Inexpensive nutrients and transportation costs, and great advances in animal production technologies led to a tremendous expansion of large livestock operations, many of which relied increasingly on imported feeds. In many industrializing regions of the world (e.g., China and India), higher incomes have greatly increased the demand for meat, milk, and other animal products. This trend of tremendous livestock expansion (a.k.a The Livestock Revolution; Steinfeld et al., 2010; Gerber et. al., 2010) raises concern over excessive nutrient use, nutrient loss, and environmental contamination (Steinfeld et al., 2006; Wang et al., 2010; Ma et al., 2010).

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On farms where livestock numbers exceed home-grown feed supplies, reliance on feed imports increases, capabilities to effectively recycle manure nutrients diminish, and the risks of water, air, and land contamination increase. To mitigate environmental risks, governments in Western Europe and North America enacted legislation to control livestock expansion and manure land-spreading practices. In the United States, rules within The Clean Water Act were updated to include guidelines for the land application of animal manure to protect lakes and streams against runoff from agricultural land. The focus of these rules was on manure P management because the control of P (pollutant source) is considered essential to the protection of surface water quality (c.f., Sharpley et al., 1994). The Clean Air Act was updated later to abate the emission of NH_3 and other hazardous gasses from livestock farms. Atmospheric NH_3 combines with other chemicals to form particulates which are harmful to human health, and the deposition of NH_3–base compounds acidifies and fertilizes natural ecosystems which lead to their degradation. The control of urea (pollutant source) contained in dairy cattle (*Bos taurus*) urine is considered a critical first step in mitigating NH_3 emissions from dairy farms (Burgos et al., 2010; van Duinkerken et al., 2011; Powell et al., 2011c).

During the mid-1990s there was a call for soil scientists to engage more closely in collaborative research with biologists, engineers, and social scientists to solve problems outside the traditional soil science area (Wagenet and Bouma, 1996). A recent white paper (Or et al., 2011) by members of the Soil Science Society of America again called for a much broader engagement of soil scientists in societal challenges (e.g., environment, climate change, food security) embraced currently by the wider scientific community. Recycling waste including animal manure is one of eight critical issues facing humanity over the next decades that require broader soil science expertise (Janzen et al., 2011).

Transdisciplinary research addresses issues that cannot be solved by one or even a few points-of-view (Wikipedia, 2011). It brings together research scientists, field practitioners, political leaders, business owners, producers, consumers, and other stakeholders to solve some of the pressing problems facing the world, from the local to the global. Using a decade of transdisciplinary dairy nutrition–soil science research conducted in Wisconsin, this paper takes a case study, chronological approach to describe pressing environmental challenges and information needs of the U.S. dairy industry, the transdisciplinary research responses, and how relationships among dairy cow rations, milk production, manure chemistry, and environmental outcomes were used to enhance profits and facilitate environmental compliance. The paper proceeds to discuss some of the ingredients to the success of these efforts including issues and opportunities for similar transdisciplinary soil science research.

NEED FOR TRANSDISCIPLINARY RESEARCH

During the middle part of the 20th century, the use of inorganic fertilizers became widespread, feeds were abundant, livestock farms became larger, and manure became a "waste" that needed to be disposed of with minimal cost. Great engineering efforts were devoted to the design, construction, and management of large and costly manure collection and storage systems. Research and extension efforts were focused on manure application practices, including when, where, and how much to apply. During the latter part of 20th century, in response to environmental concerns, large livestock farms (a.k.a., concentrated animal feeding operations) were required to develop and implement CNMPs, which included an accounting of the P and N contained in manure, and to meet new water and air quality standards. Issues related to environmental compliance created immediate dairy industry needs for information and technologies that would facilitate P and N management. The transdisciplinary dairy nutrition–soil science research described in this paper was initiated to provide information on impacts of dairy cattle rations on manure chemistry and the abilities of producers to comply with environmental standards.

Regulations on manure land spreading practices were enacted during the late 1990s to protect lakes, streams, and other surface water bodies from runoff and environmental contamination. The USDA's Natural Resources Conservation Service offered two manure land application guidelines (USDA-NRCS, 1999). The preferred guideline was the use of soil-specific P threshold values, which linked levels of STP to losses of soluble P in runoff. If information on P threshold values was not available, then determination of manure P application rates could be based on STP and anticipated levels of crop P removal. A P risk index (Lemunyon and Gilbert, 1993) was also proposed which included information on STP, the amount and method of manure application, soil erosion and runoff, and a field's distance to a surface water body. Two common variables for all three manure application guidelines were STP and concentrations of P in manure. The functional framework for the transdisciplinary dairy nutrition–soil science research described in this paper comprised associations between nutrient sources and nutrient sinks with initial focus on impacts of concentrations of P in dairy rations (source) on manure P excretion (sink) and of manure P land applications (source) on STP (sink) and runoff P (sink). Assessments were also made of how ration and manure P sources may be managed more effectively to facilitate the implementation of mandated CNMPs.

During the early to mid-2000s environmental policy related to agriculture shifted somewhat from concerns related to water quality to concerns related to the emission of NH_3 and other hazardous gasses from livestock operations. The high-profile report "Air Emissions from Animal Feeding Operations" by the National Academy of Sciences (NRC, 2003) made an urgent call for processed-based research that could assist producers and regulatory agencies in developing strategies that would abate harmful air emissions from livestock farms. For the dairy industry, the main concern was the emission of NH_3, which is generated from the large amounts of urea contained in the urine excreted by dairy cows. A new phase of transdisciplinary research was established to evaluate relationships between the type and amount of CP in lactating dairy cows rations (source) and urinary urea excretion (sink), and between urinary urea (source) and NH_3 emissions from dairy barns (sinks) and soils (sinks).

To describe the role of soil science in transdisciplinary research, the following sections provide brief overviews of key findings related to concentrations of P and CP (N × 6.25) in lactating dairy cow rations, manure chemistry and environmental outcomes, and how this information was used by the dairy industry to enhance profits and facilitate environmental compliance. Toward the end of the paper, two additional examples are given of transdisciplinary dairy nutrition–soil science research: potential impacts on soil N cycles of shifting from alfalfa (lucerne, *Medicago sativa* L.) to corn (maize, *Zea mays* L.) silage in dairy cow rations, and the impacts on milk production, manure chemistry, and abatement of NH_3 emission from dairy barns and soils by adding more tannin to dairy cow rations.

Ration Phosphorus Impacts Manure Phosphorus Chemistry and Soil Phosphorus Cycles

Until only recently in North America and Western Europe, concentrations of P in dairy cow rations were at least 20 to 25% in excess of recommendations (Satter et al., 2005). A few reasons were identified for this practice including a paucity of information regarding the minimum amount of ration P needed for high producing dairy cows to prevent deficiency symptoms, including impaired reproductive performance. This made it difficult to know how much P should be fed to provide a reasonable margin of safety above bare minimum requirements. Dairy nutrition research established that ration P recommendations (NRC, 2001) not only met the requirements, but also provided an adequate margin of safety (c.f., Wu and Satter, 2000; Wu et al., 2000; Satter et al., 2005). Another reason for excessive ration P was related to the notion that high levels of P were required to enhance the reproductive performance of dairy cows. However, research also demonstrated that feeding P in excess of recommendations had no effect on reproductive performance of dairy cattle (Satter et al., 2005).

Transdisciplinary dairy nutrition–soil science research discovered that the mineral P (e.g., monosodium phosphate, dicalcium phosphate) added to dairy cow rations had no impact on animal performance but increased the concentrations of total P and soluble P in manure (Fig. 1a), which increased soluble P in runoff (Fig. 1b) from fields after manure land application. Increases in manure P excretions due to mineral P supplements also increased the cropland area dairy farmers needed to spread manure, based on the new P-based CNMP requirements (Powell et al., 2001). Manure P increases due to excessive ration P also elevated the P/N ratio of manure. When manure land applications are based on crop N requirements, this elevated P/N ratio leads to excessive manure P applications, which increases STP (Fig. 2). The simple practice of adopting NRC's recommendations (NRC, 2001) related to concentrations of P in rations would reduce the land area in positive P balance on Wisconsin dairy farms by approximately two-thirds, which would greatly facilitate P-based CNMPs (Powell et al., 2002).

Ration Crude Protein Impacts Ammonia Emissions and Soil Nitrogen Cycles

Dairy cows excrete urea N in urine, which is a source of NH_3 emission into the atmosphere. Of the total feed N consumed by lactating cows on commercial dairy farms, a general range of 20 to 35% is secreted in milk (Jonker et al., 2002; Chase, 2004; Powell et al., 2010), and the remainder is excreted about equally in feces and urine (Kebreab et al., 2010). Ration formulation may influence not only feed N transformation into milk but also the proportion of N excreted in feces and urine. As dietary

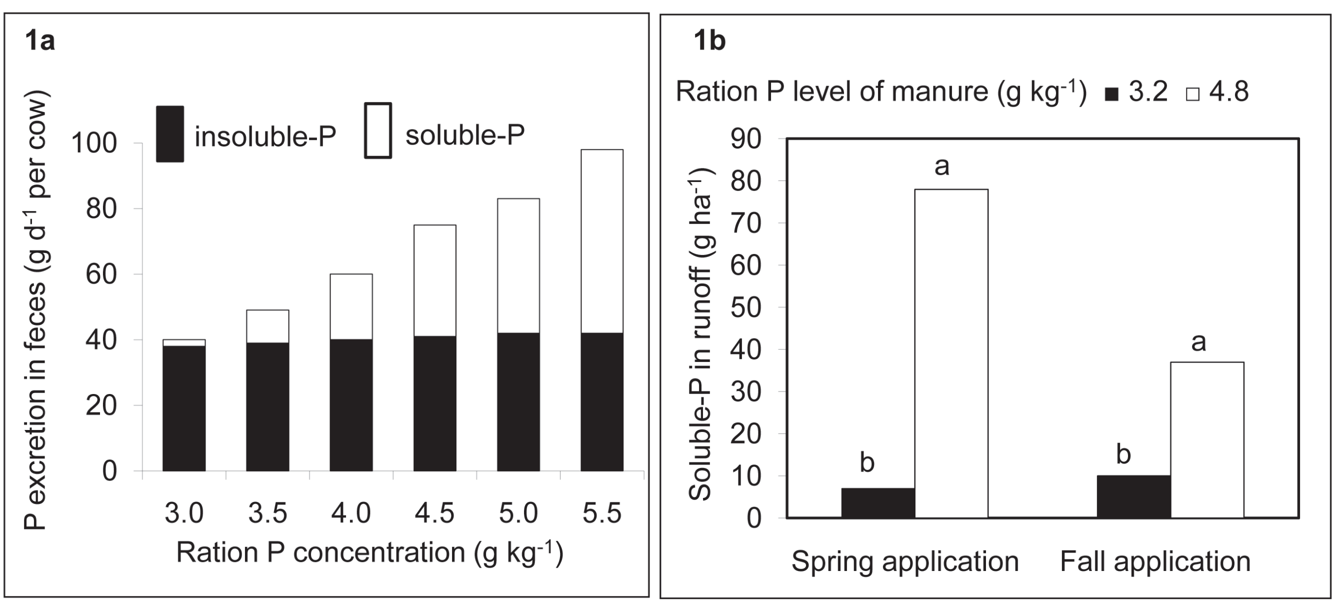

Fig. 1. Relationships between dairy ration P concentration, (a) P excretion in feces (adapted from Satter et al., 2005), and (b) runoff P after manure application to soil (adapted from Ebeling et al., 2002). Within a ration P concentration, runoff P bars having different letters differ significantly ($P < 0.05$).

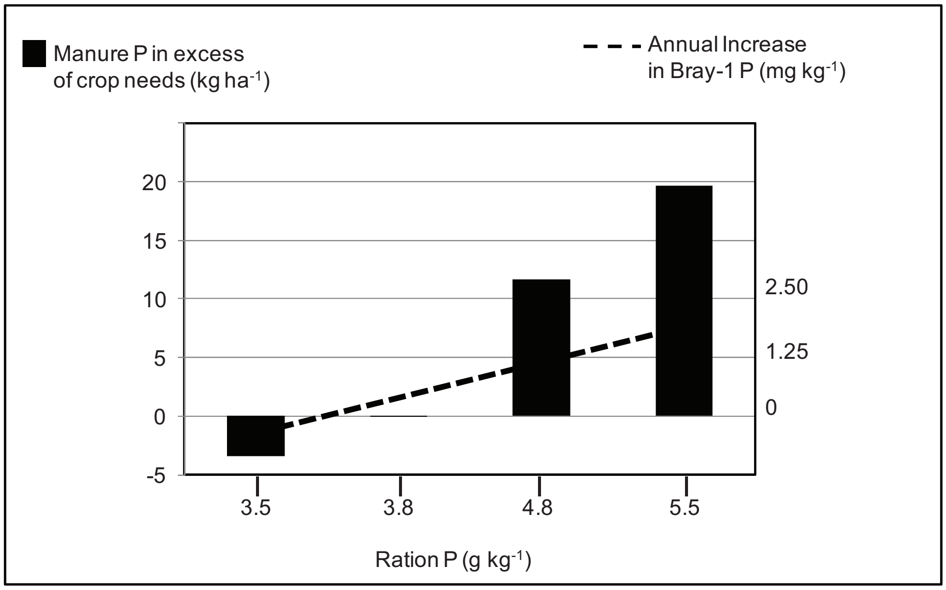

Fig. 2. Impact of dairy ration P concentration on manure P land applications and Bray-1 soil test P levels (responses when manure is land applied to meet crop N requirements [adapted from Powell et al., 2001]).

barns (sinks) and soils (sinks). Initial results revealed that increasing ration CP from 135 to 194 g kg^{-1} had few significant impacts on milk, fat, or protein yield, but decreased feed N use efficiency from 36.7 to 25.5%, and increased urea N excretion from 63 to 208 g d^{-1} per cow (Olmos Colmenero and Broderick, 2006). After application to soil, manure from cows fed a higher CP ration emits significantly greater amounts of NH_3 than manure from cows fed a lower CP ration (Fig. 3).

When lactating cow rations are balanced for their concentrations of energy and CP, approximately one-half of the total N excreted in manure is urinary N and the other one-half is fecal N. The N contained in dairy feces can be divided into two pools: (i) endogenous N originating from microorganisms and/or microbial products from the rumen, small intestine, plus hind gut, and N from the digestive tract itself; and (ii) fiber N. After application to soil, fecal endogenous N mineralizes quickly, but fiber N, having already resisted digestion by rumen microorganisms, is degraded slowly by soil microorganisms.

CP increases and N intake exceeds requirement, feed N use efficiency (i.e., the relative amount of consumed feed N that is secreted as milk N) declines and the excretion of urinary N increases (Broderick and Clayton, 1997; Nousiainen et al., 2004). Urea N comprises from 55 to 80% of total urinary N, depending on the concentration of CP in the ration (Olmos Colmenero and Broderick, 2006). Urease enzymes which are present in feces and soil rapidly hydrolyze urea to ammonium, which can be converted quickly into NH_3 gas and lost to the atmosphere. Thus, the increase in urea N excretion due to excessive CP in dairy rations increases NH_3 emissions during the collection, storage, and land application of manure (c.f., Rotz, 2004; Misselbrook et al., 2005; Powell et al., 2008; Arriaga et al., 2010).

Transdisciplinary dairy nutrition–soil science research was expanded from issues related to impacts of ration P on water quality and CNMPs to include evaluations of impacts of ration CP (source) on urea N excretion (sink), and the subsequent impacts of urea N excretions (source) on NH_3 emissions from dairy

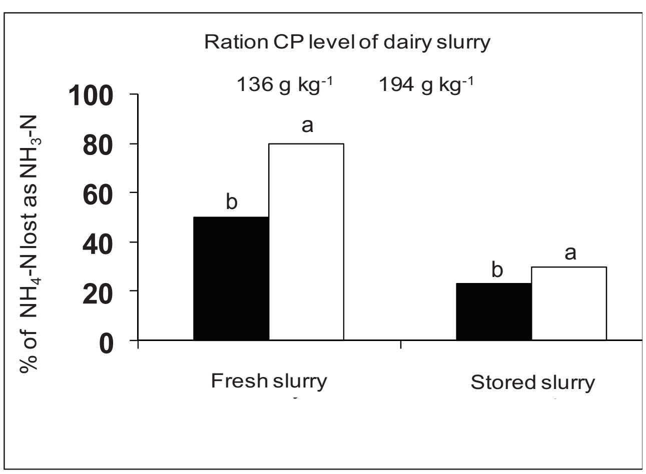

Fig. 3. Impact of ration CP concentration on NH_3 emission from soil after slurry application (adapted from Misselbrook et al., 2005).

The concentration of CP in the ration and the type and amount of forage fed impacts the relative amount of endogenous N and fiber N excreted in dairy feces (Powell et al., 2009), which in turn impacts the availability of fecal N for crop uptake. For example, compared to feces from rations containing 167 g CP kg^{-1}, feces from a ration containing 178 g CP kg^{-1} mineralizes more quickly in soil (Fig. 4a), which enhances plant yield and N uptake (Fig. 4b). These research results indicate that although reduced ration CP may have beneficial impacts on reductions in urea N excretion and therefore NH_3 emissions from soil (Fig. 3), there may be tradeoffs, as demonstrated by the overall reduction in plant available N in manure (Fig. 4a), which reduces plant yield and N uptake (Fig. 4b). Lower concentrations of soil inorganic N due to reductions in ration CP (Paul et al., 1998; Powell et al., 2011a) may eventually require some revisions to extension recommendations concerning manure N availability to crops.

Feeding Alfalfa Silage, Corn Silage, and Tannins Impact Soil Nitrogen Cycles and Ammonia Emissions

Over the past decade, perhaps the most significant change in dairy rations has been the shift from alfalfa silage to corn silage. The reasons for this change include higher dry matter yield and energy content, more uniform quality, and fewer required harvests. The impact of corn silage on milk production varies with relative amounts fed. An early study in Wisconsin (Moreira et al., 1999) revealed that cows fed a ration containing all corn silage as the forage component (50% of the total dry matter intake

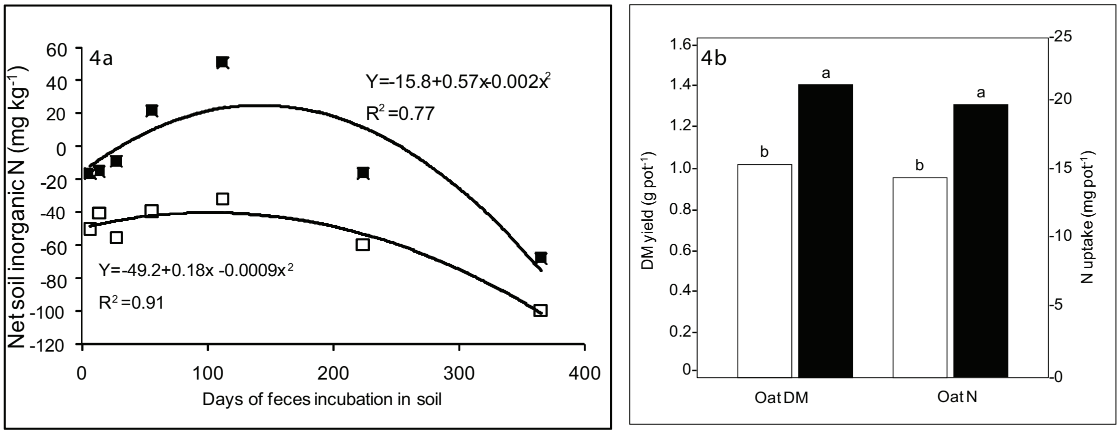

Fig. 4. (a) Plant-available N and (b) plant response to available N in Plano silt loam soil. Applied feces from cows feed either low crude protein (CP) ration (167 g kg^{-1}) or high CP ration (178 g kg^{-1}). In 4a, 'white square' refers to feces from cows fed low CP ration, and 'black square' refers to feces from cows fed high CP ration; in 4b, white bars depict feces from cows fed low CP ration and black bars refer to feces from cows fed high CP ration. Oat dry matter and oat N response bars having different letters differ significantly (P < 0.05) (adapted from Powell et al., 2006).

[DMI]) produced less milk than cows fed an equal blend of corn silage (25% DMI) and alfalfa silage (25% DMI). Later studies in Wisconsin (Wattiaux and Karg, 2004a, 2004b) determined that cows fed a higher percentage (41.2% DMI) of corn silage in the ration produced more milk but lower milk fat, and excreted less total N in manure and more N in feces than cows fed higher percentage (41.2% DMI) of alfalfa silage.

Using the manure derived from these dairy nutrition trials, transdisciplinary soil science research was expanded to evaluations of whether more corn silage in rations would impact the fertilizer value of manure and/or soil quality on dairy farms. Initial findings were that cows fed corn silage-based rations (source) excreted feces (sink) that mineralized N in soil more slowly than feces excreted by cows fed alfalfa silage-based rations (Fig. 5a and 5b). Reductions in mineralized N (source) due to corn silage feeding led to reductions in crop yield and crop N uptake (sink). We postulated that more corn silage in dairy cow rations would impact soil N cycles in two ways: (i) as corn replaces alfalfa in the cropping system, the amount of biologically-fixed N on dairy farms would decrease, which would increase the need for fertilizer N, and (ii) additional fertilizer N may be required to offset soil N immobilization and potential decrease in crop yield when manure from corn silage, rather than alfalfa silage-based rations, is land applied. These preliminary results demonstrate that although corn silage may feed more cows, it may impact overall N use, manure N chemistry, N mineralization in soil, and plant uptake of applied manure N.

Protein breakdown in alfalfa during ensiling is a major problem because dairy cows use poorly the resulting nonprotein N products. Because of poor utilization of nonprotein N, dairy cows must be fed protein supplements, which not only increases feed costs but also concentrations of CP in the ration, excretion of urea N in urine, and NH_3 emissions from dairy farms. Recent dairy nutrition research revealed that adding small amounts of a

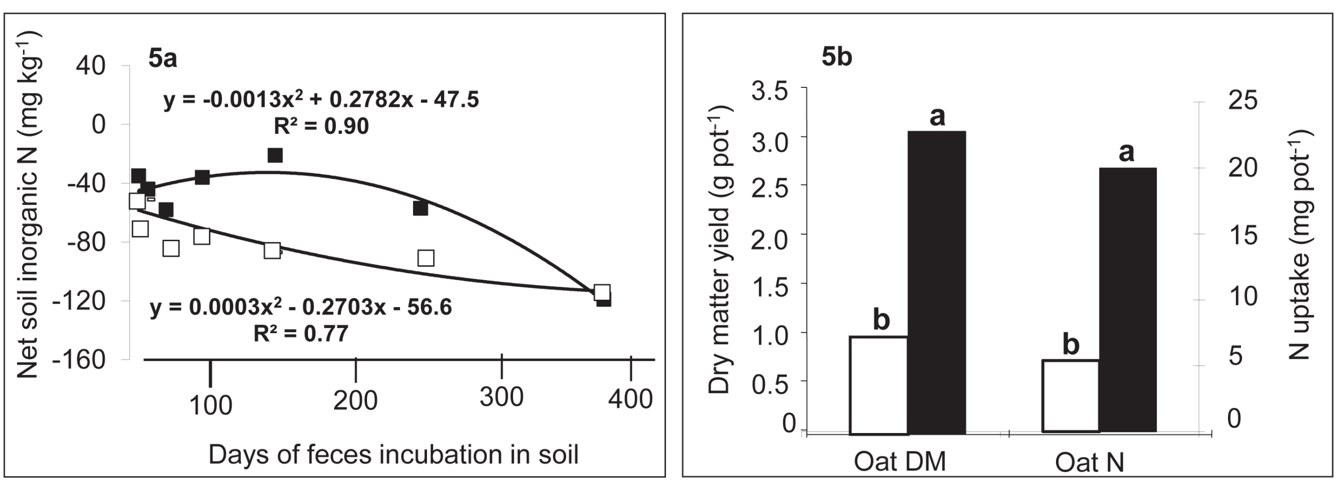

Fig. 5. (a) Plant-available N and (b) plant response to available N in Plano silt loam soil. Applied feces from cows feed corn silage and/or alfalfa silage. In 5a, 'white square' refers to feces from cows fed corn silage as the only forage, and 'black square' depicts feces from cows fed an equal proportion of corn silage and alfalfa silage; in 5b: white bars depict feces from cows fed corn silage, and black bars refer to feces from cows fed an equal proportion of corn silage and alfalfa silage. Oat dry matter and Oat N response bars having different letters differ significantly (*P* < 0.05) (adapted from Powell et al., 2006).

tannin extract (a mixture from red quebracho [*Schinopsis lorentzii*] and chestnut [*Castanea sativa* Mill.] trees) to a ration comprised of 21% alfalfa silage, 29% corn silage, and 50% concentrate does not significantly impact animal performance (Aguerre et al., 2010a) but increases feed N use efficiency and decreases urea N excretion (Aguerre et al., 2010b). Using the excreta produced by cows on this nutrition trial, recent lab-scale trials revealed that reduction in urea N excretion and urease activity in feces (Powell et al., 2011b) due to tannin extract feeding leads to dramatic decreases in NH_3 emission from dairy barns and soils (Fig. 6) and from soils after slurry application.

INGREDIENTS OF TRANSDISCIPLINARY SOIL SCIENCE RESEARCH

There are four interrelated ingredients to the transdisciplinary dairy nutrition–soil science research reported in this paper: (i) an immediate and clear need for the information, (ii) the required expertise of both dairy nutrition and soil science to provide this information, (iii) the ability and willingness of scientists, state extension staff, and dairy producers to work together, and (iv) available funding. Related to the first two points, the new water quality regulations based partially on manure P management, and the new air quality standards based partially on NH_3 emission, created immediate needs for information on relationships between concentrations of P and CP in dairy rations and how these components may be modified to satisfy the nutritional demands of healthy, high producing dairy cows, while at the same time reduce total concentrations and labile forms of P and N in manure. Determinations of how ration components impact milk production, profits, manure chemistry, and water and air quality required transdisciplinary dairy nutrition–soil science research. Neither dairy nutrition nor soil science alone could have provided this information to the dairy industry.

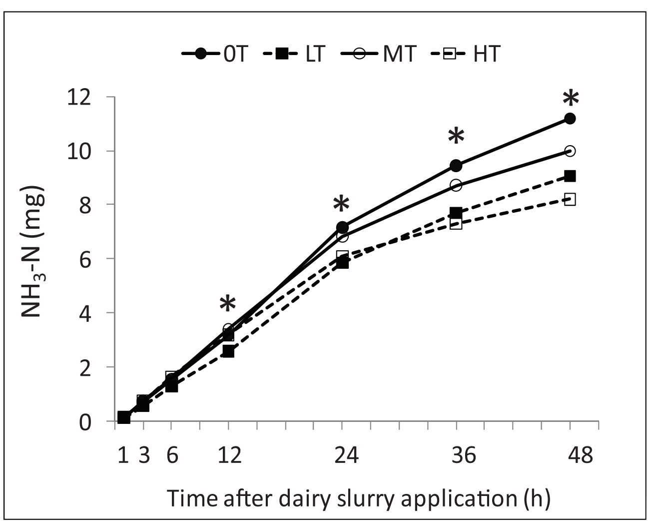

Fig. 6. Impact of tannin feeding on cumulative NH_3 emission from soils after slurry application (0T, LT, MT, and HT refer to dietary tannin extract levels of 0, 4.5, 9.0 and 18.0 g kg^{-1} of dry matter intake, respectively. * above data points refer to significant differences at $P < 0.05$; adapted from Powell et al., 2011a).

In addition to dairy nutrition and soil science expertise, the transdisciplinary research also included expertise in social science to understand what, how, and why feed and manure management decisions were made by commercial dairy farm operators. Three studies were conducted on commercial dairy farms to determine prevailing concentrations of P and CP in lactating cow rations, to understand the factors producers considered while making feed and manure management decisions, and to identify the challenges and opportunities producers may face in environmental compliance. Of particular interest to dairy producers and their nutrition consultants were comparisons of feed use efficiencies achieved on their farms to the feed use efficiencies obtained on other farms, and discussions related to win-win practices that would enhance feed conversion into milk, reduce feed costs, and facilitate environmental compliance. For example, the elimination of unnecessary inorganic P supplements in dairy rations was particularly attractive to producers in that it would both reduce feed costs and manure P excretions, which would facilitate the development and implementation of their CNMPs. The transdiciplinary dairy nutrition–soil science research provided information to extension (IPNM, 2009) that was used to convince dairy producers, the feed industry, and veterinarians to reduce ration P levels. For example, the mean P content in samples of total mixed rations fed to dairy cows in Wisconsin has decreased from 4.1 g kg^{-1} in 2004 to 3.6 g kg^{-1} in 2010 (UW-Soil & Forage Lab, 2011), which indicates that dairy cows are now being fed closer to NRC recommendations (3.6 g kg^{-1}) than in the past. A recent impact analysis (USDFRC, 2010) determined that reduced ration P by elimination of unnecessary mineral P saves the U.S. dairy industry between $109 and $180 million annually, and that reduced ration CP through reduction of unnecessary supplements would save an additional $740 million annually.

Related to the third point, the transdiciplinary efforts required a functional framework that linked multiple interests and therefore created motivation for diverse stakeholders to work together. For example, dairy nutritionists and soil scientists were willing and able to expand their conventional research approaches, usually based on dairy rations that maximized economic returns, and manure management that minimized costs to include new aspects of environmental outcomes and accountability. The research framework that linked ration components (sources) to manure components (sinks), and manure components (sources) to water and air quality (sinks) provided cohesive, functional linkages in the transdisciplinary research efforts. From an extension perspective, the transdisciplinary research provided experimental and on-farm results that were novel and practical, so they were incorporated immediately into an array of new training materials. For example, fact sheets were published and feed management was incorporated into Wisconsin-wide extension training programs (IPNM, 2009). The convincing linkages between dairy nutrition and manure chemistry were catalysts to the incorporation of feed management into national curricula for CNMPs (USDA-NRCS, 2010).

Related to the fourth point, three competitive grants were awarded to partially support this transdisciplinary research: two USDA National Research Initiative (NRI) grants under the Agricultural Systems Program to fund 6 yr of research on "A Systems Approach to Phosphorus Management on Dairy Farms", and a USDA Initiative for Future Agricultural and Food Systems (IFAFS) grant to fund 4 yr of research on "Enhanced Integrated Nutrient Management on Dairy Farms". The USDA's National Institute for Food and Agriculture (NIFA) currently devotes up to 20% of the value of its competitive grant portfolio on projects that integrate research, education, and extension (USDA-NIFA, 2011). The NIFA's Coordinated Agricultural Project (CAP) grants support large-scale multimillion dollar regional projects to conduct targeted research, education, and extension in response to emerging or priority area(s) of national need. It is still too early to tell if NIFA's new approach to award fewer yet larger regional grants will engender the required focus on the societal issues deemed important to soil scientists (Or et al., 2011; Janzen et al., 2011). Larger multi-institutional grants may mean less money available to smaller transdiciplinary research teams (such as the one described in this paper), and may increase the transaction costs of doing research (i.e., more overhead associated with subcontracts across many partner institutions). With prevailing federal budget constraints, funding levels for all agricultural research remains highly uncertain.

CONCLUSIONS

During the last part of the 20th century, animal waste management became an environmental concern. This led to regulations including mandated CNMPs, which required an accounting of land application of manure nutrients. To address the need for information and practices that would assist dairy producers in environmental compliance, transdisciplinary dairy nutrition–soil science research was initiated to determine relationships among lactating cow rations, milk and manure production, manure chemistry, and key environmental outcomes of dairy production. Source-sink relationships were used to evaluate relationships between ration sources (concentrations and forms of P and CP) and sinks (milk and manure), and relationships between manure sources (soluble P, urea N) and sinks (STP, runoff P, NH_3, soil inorganic N, crop N) and the impact of these relationships on the environmental impacts of milk production. As ration P concentrations increase, the excretion of total P and soluble P in manure also increases. Runoff of soluble P from cropland after manure application, which can pollute surface waters, can be related back to the P excreted in manure, which is linked to the amount of mineral P in cow rations. Likewise, the type and amount of CP and forage fed to dairy cows impact manure chemistry and manure N cycling in soil, including plant N uptake. Ammonia emissions from soil after manure application can be related back to the urea N excreted by dairy cows in urine, which is linked to the concentrations of CP in cow rations and the type of forage fed. The transdiciplinary research results demonstrate that profitable rations can be fed to satisfy the nutritional demands of healthy, high producing dairy cows, reduce manure excretion, and therefore facilitate environmental compliance by the dairy industry.

A wider use of source-sink relationships that link biological, biophysical and physical components of soils to other biosphere components may be helpful in engaging soil scientists in some of the societal challenges embraced currently by the wider scientific community. For example, the recent white paper "Securing a Future for Soil Science (Or et al., 2011) calls for a much broader definition and application of soil science research. This is derived from an array of functions and critical services provided by soils that both include and transcend food production, such as soils being the planet's life support system; the host of the largest pool of biodiversity of all global biospheres; a giant recycling system; the largest terrestrial stock of organic carbon and therefore principal buffer against global warming; a provider of important ecosystem services, such as fresh and clean water; and an integrator of the earth processes for which it is intrinsically linked. In a similar context, food security, fresh water, nutrients, energy, climate change, waste recycling, and biodiversity are considered seven of the "Eight Critical Issues Facing Humanity and How Soil Scientists Can Address Them" (Janzen et al., 2011). Each of the critical issues outlined in this paper and the white paper contains a host of source-sink relationships that may help direct soils science toward greater relevance in preserving our fragile home on the changing planet.

ACKNOWLEDGMENTS

In memory of Dr. Armand R. Van Wambeke (1926–2011) who said (as quoted in his obituary): "To make progress in soil science, one must go outside of it".

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