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Short communication: Identifying challenges and opportunities for improved nutrient management through the USDA's Dairy Agroecosystem Working Group

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ABSTRACT

Nutrient management on US dairy farms must balance an array of priorities, some of which conflict. To illustrate nutrient management challenges and opportunities across the US dairy industry, the USDA Agricultural Research Service Dairy Agroecosystems Working Group (DAWG) modeled 8 confinement and 2 grazing operations in the 7 largest US dairy-producing states using the Integrated Farm System Model (IFSM). Opportunities existed across all of the dairies studied to increase on-farm feed production and lower purchased feed bills, most notably on large dairies (>1,000 cows) with the highest herd densities. Purchased feed accounted for 18 to 44% of large dairies' total operating costs compared with 7 to 14% on small dairies (<300 milk cows) due to lower stocking rates. For dairies with larger land bases, in addition to a reduction in environmental impact, financial incentives exist to promote prudent nutrient management practices by substituting manure nutrients or legume nutrients for purchased fertilizers. Environmental priorities varied regionally and were principally tied to facility management for dry-lot dairies of the semi-arid western United States (ammonia-N emissions), to manure handling and application for humid midwestern and eastern US dairies (nitrate-N leaching and P runoff), and pasture management for dairies with significant grazing components (nitrous oxide emissions). Many of the nutrient management challenges identified by DAWG are beyond slight modifications in management and require coordinated solutions to ensure an environmentally and economically sustainable US dairy industry.
Key words: dairy, nutrient management, phosphorus, nitrogen

Short Communication

Nutrient management that improves nutrient use efficiency, crop yields, and economic returns while reducing environmental impact is critical to the sustainability of dairy production. Holistic approaches to nutrient management consider a diversity of factors, including animal breed, diet, manure handling, storage, and recycling of nutrients as crop fertilizer. The need for change in nutrient management practices is most evident when inequalities of imports (i.e., fertilizer and feed) with exports (i.e., milk and animals) are identified (Gourley and Powell, 2007). However, air and water quality are also major drivers of nutrient management decisions (Castillo et al., 2000), sometimes prompted by litigation or regulation (Rodriguez, 2015). Given tight profit margins of US dairy [$16.15 per cwt (1 cwt = 50.8 kg) of milk sold with operating costs of $14.44 per cwt in 2016 (profit margins of $0.32 per kg of milk and $0.28 operating costs); USDA-ERS, 2017] and environmental pressures on nutrient management, understanding themes in nutrient management across the United States is critical to identifying opportunities in US dairy agriculture.

The US Department of Agriculture, Agricultural Research Service (USDA-ARS) Dairy Agroecosystems Working Group (**DAWG**) is a research collaboration established in 2014 to support efforts to improve the productivity, competitiveness, and environmental sustainability of US dairy farming systems. The group includes research teams focused on the major dairy-

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producing regions of the western (California, Idaho, Texas), midwestern (Minnesota, Wisconsin), and eastern (New York, Pennsylvania) United States. Research from DAWG members has provided insight into the scope of nutrient management concerns on dairy operations, including feeding strategies to better balance nutrients and improve dietary nutrient use efficiency (Rotz et al., 1999, 2002; Powell, 2014); farmstead management to control emissions and discharges of nutrients (Penn and Bryant, 2006; Leytem et al., 2009; Krueger et al., 2013); and manure management to improve crop nutrient recovery, reduce environmental losses, and sequester carbon (Powell et al., 2011; Waldrip et al., 2012; Gamble et al., 2017).

Currently, there is a paucity of information on the differences in N and P dairy farm balances at the farm gate, including all imports and environmental losses, between the major dairy production regions of the United States. To quantify key nutrient management challenges facing dairy producers across the United States, the Integrated Farm System Model (**IFSM**; USDA-ARS, 2017) was used to conduct whole-farm simulations of operations where DAWG has actively conducted research. We hypothesize that the interaction of climate and dairy production strategy affect pathways of nutrient loss and the magnitude of nutrient losses across selected US dairy regions. Ten farms were modeled, highlighting common dairy farming strategies, from the top 7 milk-producing states in the United States (USDA-NASS, 2016; Figure 1). Based on the farm sizes used and the 2012 US Census of Agriculture (USDA-NASS, 2012), the selected simulations accounted for 16 to 96% of the dairy herd of the 7 selected states or 21% of the US dairy herd (Table A1 in Appendix). Simulations were conducted over a 25-yr sample of recent historical weather to account for climate-dependent performance variability. Results were used to highlight current nutrient use inefficiencies on dairy farms across the United States that must be prioritized for subsequent optimization.

The IFSM has been extensively applied to dairy production systems, simulating crop production, feed use, manure handling, storage and application, and other major activities related to nutrient management of dairy farms (Rotz et al., 2016). Nutrient flows are tracked through the farm, from housing facilities, to manure storage, and to the field on a daily basis (Rotz et al., 2016). Annual whole-farm mass balances of N and P are determined at the farm gate for major pools and pathways of farm import and export, including imports in feed, fertilizer, atmospheric deposition, and legume fixation and exports in milk, excess feed, animals, manure, and environmental losses. Modeled environmental P losses are sediment P runoff, soluble P runoff, and P leached; environmental losses of N are N leached, N runoff, nitrified/denitrified N (gaseous emissions of N_2O, NO, and N_2), and N volatilized (ammonia emissions). Routines for gaseous emissions, leaching, runoff, feed production and use, resource requirements, and economics within IFSM have been evaluated in previous studies of dairy production systems, including studies in the vicinity of the farms included in this study (Rotz and Oenema, 2006; Rotz et al., 2011, 2014; Belflower et al., 2012). Notably, simulated nutrient losses of the 10 farms compared well with published observations from empirical studies on dairy farms (Appendix, Table A2).

The IFSM includes a whole-farm budget of annual production costs and income for simulated farms (Rotz et al., 2016). Operating costs associated with resources used for crop and animal production include land, fuel, repairs, fertilizers, seed, chemicals, insurance, milk hauling, milk marketing, custom operations, and livestock expenses. Fixed costs include facilities and machinery expenses where initial costs are amortized to annual values considering salvage value, real interest rate, and useful life. Hired and unpaid labor costs were obtained from the USDA Economic Research Service's report on cost-of-production using the appropriate cost with farm size (Macdonald et al., 2007). Prices were averaged for the previous 5 yr to account for market fluctuations to obtain relative prices. Farm income derives from the sale of excess feeds, milk, and animals.

Dairies included in the DAWG analysis provide examples of common dairy production systems for each region (Appendix Table A1). Simulated milk yields of individual farms spanned nearly 2 orders of magnitude (924 to 81,000 t/yr = 18,200 to 1.6 million cwt/year), although the yields per cow ranged by 30%: 8,400 to 11,990 kg/cow per year of fat- and protein-corrected milk (FPCM). The largest operations were located in semi-arid western states (CA, ID, and west TX), where the 4 dairies ranged in size from 2,000 to 7,000 milk cows/herd. Manure was handled as a solid and liquid at these dry-lot dairies, with manure collected through dry-lot manure removal and flushing of feed lanes, respectively. In contrast, the humid midwestern and eastern states (MN, WI, PA, and NY) had smaller dairies ranging from 100 to 5,500 cows/herd. Cattle housing common to these regions was freestall and tiestall configurations, with liquid, slurry, or semi-solid manure handling, resulting in manure that is more difficult and expensive to transport over long distances than dry manures. Farms chosen to illustrate the variability of dairy operations within regions included a freestall dairy found in humid central Texas (1,000 milking cows), a small dry-lot dairy located in Idaho (280 milking cows), and a grazing dairy operating in Pennsylvania (100 milking cows).

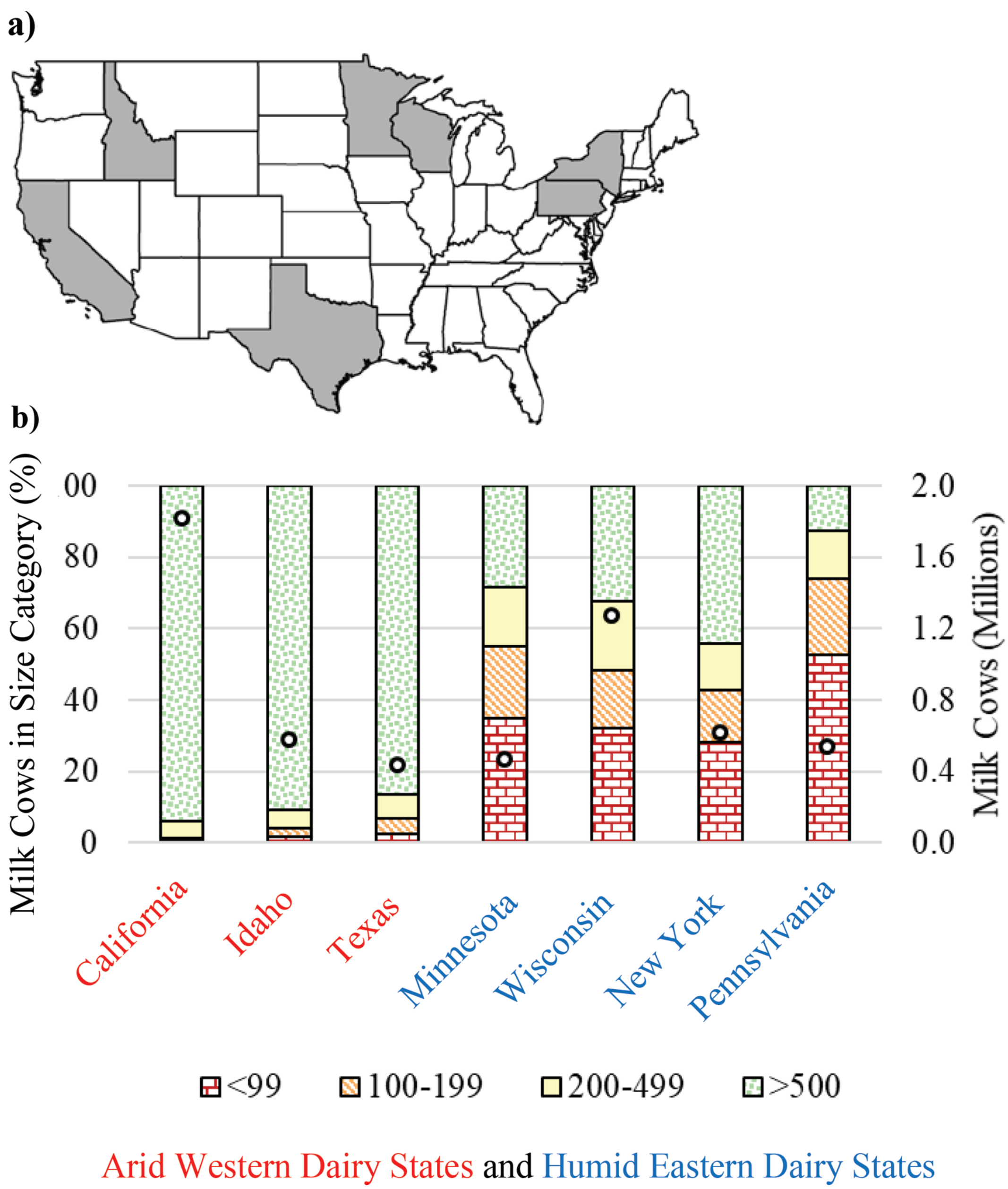

Figure 1. (a) The 7 major US dairy states (arid western states: CA, ID, TX; humid eastern states: MN, WI, NY, PA) evaluated in the USDA Agricultural Research Service Dairy Agroecosystems Working Group (DAWG) study and (b) their dairy herd sizes and milk cow populations. Color version available online.

Total cost of production per unit of milk produced was lower on the large dairies with more than 1,000 milk cows (\$287/t milk) than on the smaller dairies (\$377/t milk), confirming different financial capacities to adjust nutrient management strategies and a potential role for cost substitution in motivating management changes on small dairies. The relative costs of feed and fertilizers, the most direct form of nutrient management expense, varied largely as a function of herd density (cows/ha). For large dairies that also tended to have the greatest herd densities, purchased feed was a greater expense (25 to 44% of total costs) compared with the cost of purchased feed on small dairies (7 to 14%) due to greater homegrown feed production.

Nitrogen fertilizer costs were generally at least 3 orders of magnitude greater than P fertilizer costs, demonstrating greater potential to realize cost reductions in N fertilizer management rather than P fertilizer management. Although not a major contributor to overall operating costs, the cost of N fertilizers was

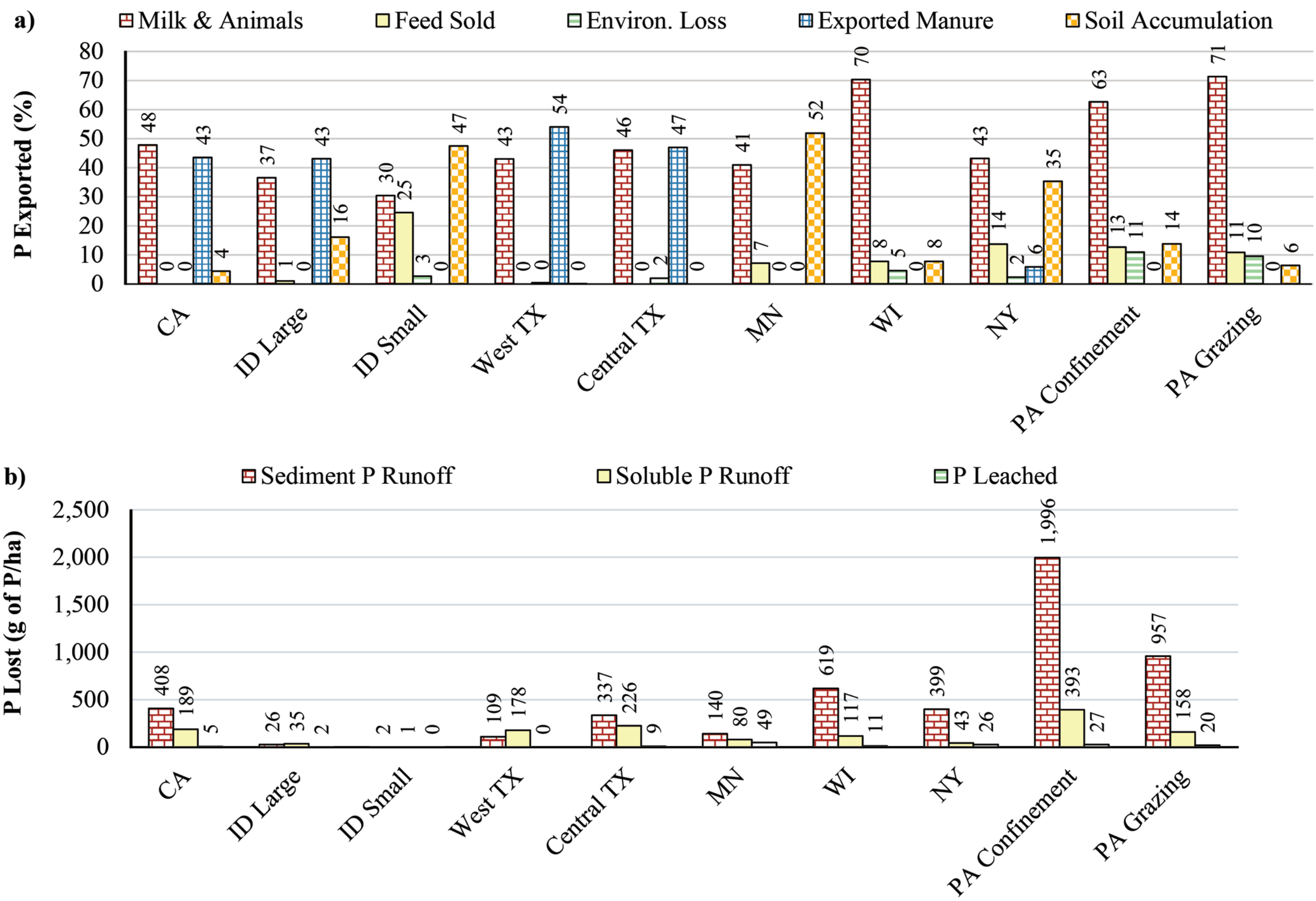

Figure 2. Simulated P exports from dairy farms relative to farm-gate P imports (a) and environmental P losses (b). Color version available online.

an important expense to dairies, ranging from $2,900 to $185,500/yr (Appendix Table A3). Nitrogen conservation at the farm gate would reduce imports of N fertilizer to supplement crop growth and decrease N fertilizer purchases. Eliminating commercial N fertilizer use through more efficient use of manure N has the potential to reduce total cost per ton of milk by 0.4 to 4.9%, with a higher potential for profit gain on dairies in the western United States (Appendix Table A3).

Today, P management is largely viewed as an environmental concern across the US dairy industry. Agronomically and economically inconsequential losses of P from farms (e.g., 1 kg of P/ha) can significantly degrade downstream water quality because of the disproportionate sensitivity to P of freshwater ecosystems compared with terrestrial ecosystems (Carpenter et al., 1998). Therefore, maintaining a balance of P at the farm gate is an important long-term strategy for preventing the accumulation of manure P in farm soils, a long-term source of P to runoff water (called "legacy P"), which is one of the most difficult environmental problems for farmers to address (Sharpley et al., 2013). Across the DAWG study's 10 farms, the greatest opportunities to prevent on-farm accumulation of P were associated with the export of dry manures from the large, open-lot dairy systems of California, Idaho, and Texas, where 43 to 54% of purchased P in feed and fertilizer was exported in products in manure and compost. In comparison, the liquid manure management systems of confinement dairies in the more humid areas (MN, PA, central TX, WI) restricted opportunities for manure export, resulting in greater accumulation of P in farm soils (Figure 2a). Opportunities to better balance P at the farm gate include dairy ration management to improve feed P conversion efficiency into marketable products (Knowlton et al., 2010), greater reliance upon forages produced on-farm (Ghebremichael et al., 2008), prudent subscription to soil fertility recommendations to minimize unnecessary application of purchased P fertilizer (Ketterings et al., 2011), and liquid manure processing technologies, such as solids separation, that enable export of transportable fractions of manure solids (Van Horn et al., 1994; Church et al., 2016).

Simulated environmental P losses were, at most, 11% of the total amount of P imported at the farm gate (Figure 2a). Phosphorus runoff loss, although a minor influence to overall farm-gate P balances, was a concern for surface water, with losses ranging from 3 to 2,000 g of P/ha (Figure 2b). The majority of P runoff was associated with sediment runoff. Results point to industry potential to continue to improve water quality outcomes through established strategies such as 4R nutrient stewardship (right source, right rate, right time, right place; IPNI, 2013) to reduce runoff and riparian buffers to capture P at the edge of field (Havlin, 2004). Indeed, lower runoff P losses were consistently predicted when production strategies incorporated manure the same day as it was applied either through tillage or subsurface injection (NY, large ID, and MN). In semi-arid regions, low precipitation (<300 mm/yr) limited P losses, such as from the Idaho dairies. Differences in sediment-bound P loss observed between farms of close geographic proximity (e.g., the grazing versus confinement dairies in PA and TX) highlight the persistent need to emphasize soil conservation in dairy production, including reduced tillage and crop rotations that promote perennial living cover (Bosch et al., 2006). The emergence of soil health as a rubric for field management deserves full investigation by the dairy industry (Doran and Zeiss, 2000).

Exports of N through milk and animal sales were 21 to 37% of all N imported onto the farms (Figure 3a). Opportunities for greater on-farm feed production directly affect farm N balances; farms with the lowest purchased imports of N (CA, MN, WI, and both PA dairies) had the highest percentage export of imported N in milk and animals sold. Environmental N losses were equivalent to 50 to 77% of N imported annually

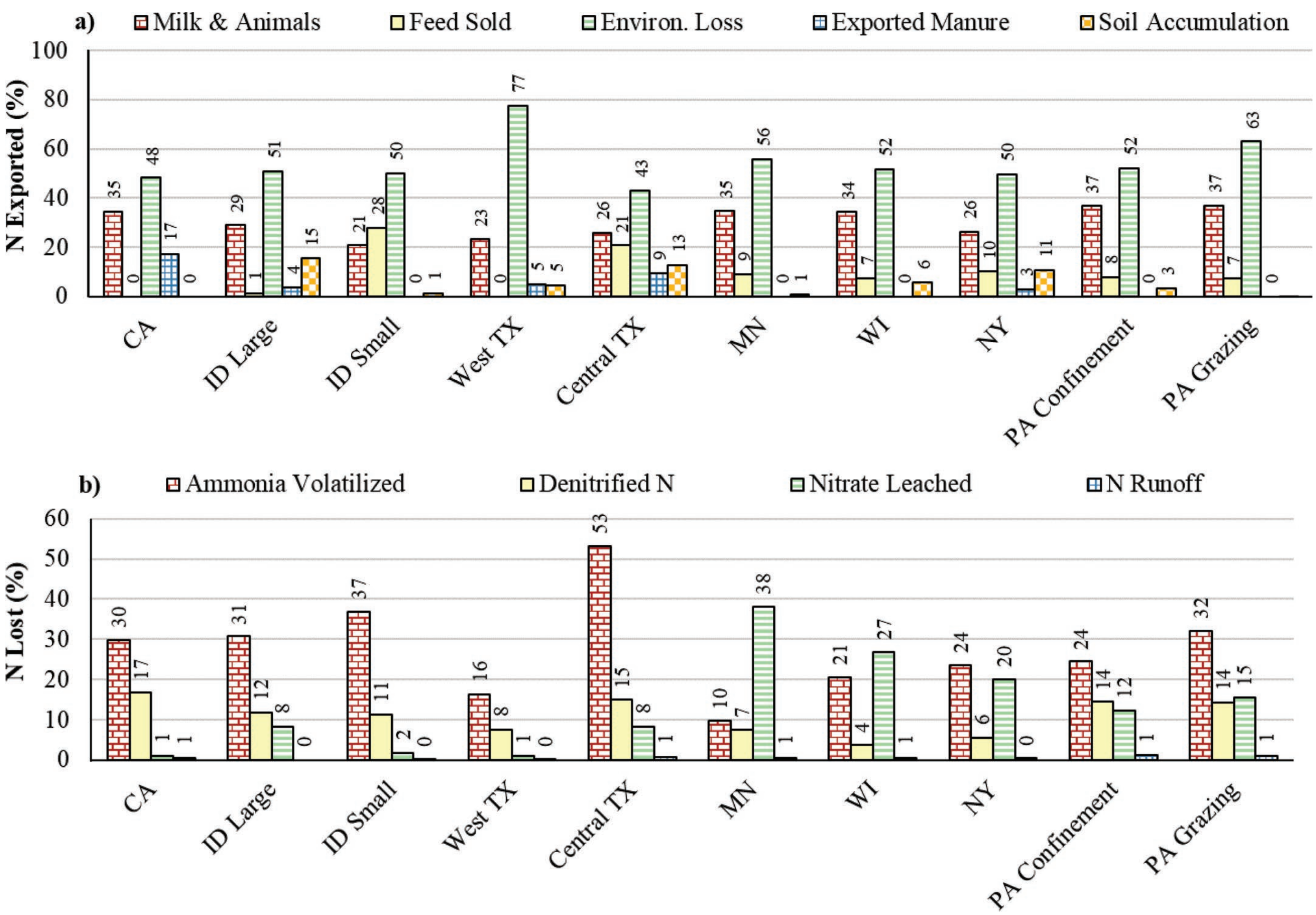

Figure 3. Simulated N exports from dairy farms as a function of farm-gate N imports (a) and environmental N loss by N source (b). Color version available online.

onto the farms, the majority of which was by ammonia volatilization, followed by nitrate leaching and denitrification loss pathways (Figure 3a and b).

Ammonia management must be seen, primarily, as a consequence of diets with protein (nitrogen) fed in excess of that required by the animal, resulting in the excretion of excess N in the form of urea, the initial and primary source of ammonia (Monteny and Erisman, 1998). Thus, the improved efficiency of feed N conversion to milk N remains a priority for all dairy systems (Jonker et al., 2002). Across all 10 DAWG study farms, ammonia losses were greatest from the dry-lot dairies of the western states (Figure 3b), equivalent to 30 to 51% of total N imported to the farm, and lower from the confinement and grazing dairies of the midwestern and eastern states (10 to 32% of N imported). Differences in ammonia loss between the operations and between regions are principally a function of climate, facility, and manure management (Bjorneberg et al., 2009; Leytem et al., 2011; Bougouin et al., 2016). At present, proven technologies exist to reduce ammonia emissions from freestall and tiestall dairies of midwestern and eastern United States (e.g., acidification of manure, reduced-CP diets, and slurry injection as reported in Hou et al., 2015), but fewer abatement strategies have been proven for the outdoor housing surfaces of the arid western states (57 to 78% of dry-lot dairies' ammonia N losses). Chemical amendments (DeLaune et al., 2004) can reduce ammonia emissions from other dry manures (poultry); however, their success is reduced by short-term effectiveness and economic cost of reapplication on open lot facilities.

Because of the labile nature of N, conservation of ammonia does not equate to better use of remaining N on dairy farms. In fact, ammoniacal-N that is conserved on farms is at risk of nitrate leaching following nitrification, or volatilization following subsequent denitrification (Jensen, 2013). Markedly, nitrate leaching from dairies in humid midwestern and eastern regions was estimated to contribute more to environmental losses of N (12 to 38% of imported N) than it did in western dairies (1 to 8% of imported N), a result of generally greater additions of manure N to soils and greater precipitation. Results of the simulations across the 10 farms confirm a persistent need for dairies in the midwestern and eastern United States to mitigate nitrate leaching by adjusting cropping systems to better recover N year round (Dinnes et al., 2002), and manage manure following 4R nutrient stewardship principles (IPNI, 2013). Denitrification is a greater concern to N loss from the western dry-lot dairies (loss of 11 to 24% of imported N) and from dairies using pastures (14 to 23%) compared with confinement dairies of Minnesota, Wisconsin, and New York (7 to 4%). Denitrification losses from dry-lot dairies were primarily tied to housing facilities and manure management, with limited options to currently consider for mitigation (e.g., El Kader et al., 2007). Grazed pastures are known to have higher nitrous oxide emissions than croplands, reflecting disproportionate emissions of nitrous oxide from urine patches (Oenema et al., 1997; Saggar et al., 2004; Hyde et al., 2006). Here, options for mitigation of denitrification losses include use of urease and nitrification inhibitors (Zaman and Blennerhassett, 2010), adjustment of sward composition (Ledgard et al., 1998), and restricted grazing during wet seasons (de Klein et al., 2006).

Through its national perspective on US dairy production systems, DAWG simultaneously highlights a heterogeneous industry that challenges uniform solutions to environmental issues, and ascertains common themes in nutrient management that provide opportunities for broad industry action. Certainly, opportunities for improved nutrient management exist across all of the dairies studied by DAWG to increase on-farm feed production, most notably on large dairies with highest herd densities where there is greatest opportunity to lower purchased feed bills by farming more land and recycling more manure nutrients. In addition, there is a widespread need to improve dietary formulations to reduce overfeeding of nutrients. For dairies with greater land bases, incentives exist to promote prudent nutrient management practices by substituting conserved manure nutrients or legume nutrients for purchased fertilizers.

Ultimately, the current nutrient management opportunities identified by the DAWG analyses may not be sufficient to ensure a prosperous and sustainable US dairy industry that is under increasing pressure to reduce its environmental impact. The dairy industry needs novel, low-cost, and easily implemented and maintained solutions for reducing ammonia losses from western dry-lot dairies, including feeding lot and pen designs to minimize urine and feces contact or reducing urease activity. Similarly, midwestern and eastern dairies need new, economically feasible technologies for preventing manure nutrient losses from the field, including new technologies to enable recovery of manure components to facilitate their export, adjusted cropping systems, and 4R-specific technologies that improve the rate, timing, placement, and form of applied manures for operations large and small. All dairies with liquid manure management would benefit from technologies for extracting and concentrating manure nutrients that can then be exported from the farm, possibly creating additional profit. The challenge to agricultural research and engineering is to develop bold innovations that address these regional and industry-wide challenges.

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APPENDIX

Integrated Farm System Model

In the current study, IFSM performed well across the range of dairies covered in the study; simulated values were generally comparable to measured values, falling within or near measured ranges (Table A2). In some cases, the model has been better at representing certain processes than others, such as N leaching and volatilization in eastern no-till systems over P runoff (Rotz et al., 2011). Differences between simulated and measured confinement dairies were most likely a result of a difference in climate between simulated farms and field trials. For example, if precipitation modeled did not exceed the rate of soil infiltration, no runoff would occur and, as a result, some the simulated N and P runoff rates were lower than measured values. Soil moisture, which is expected to be lower for arid cropland, would affect nitrous oxide production and result in lower emissions from simulations for these dairies in comparison with measured values (Lazcano et al., 2016). Dry-lot facilities in the west had greater N volatilized than simulated eastern dairies and currently there is an absence of ammonia measurements at the farm scale. However, emerging literature agrees that simulated predictions from dry lots (92.8 to 121 kg of NH_3/cow) are comparable to measured annual ammonia emissions of 32 to 110 kg of NH_3/cow from dry lots (Bonifacio et al., 2015; Todd et al., 2015).

Table A1. Characteristics of representative dairy farms

Location	Annual precipitation (mm)	Herd characteristics (head)		Housing	Crops		Manure management		Milk production (kg/cow per year)	Percent of state's dairy herd based on farm size
		Milking	Replacements		Land area (ha)	Rotation	Handling/storage	Land application		
California	408	2,000	1,650	Freestall and dry lot	300	Corn/double cropped oats	Scraped, separation, lagoon	Broadcast, 1-wk incorporation	11,990	40
Idaho	275	280	244	Dry lot	223	Corn/wheat/alfalfa	Stack and runoff catchment	Broadcast, same-day incorporation	9,757	5
Idaho	275	7,000	5,700	Dry lot with flushed feed lane	3,692	Corn/alfalfa	Compost stack, lagoon	Irrigation, export 50%	10,449	90
Texas (West)	449	3,222	1,324	Dry lot	939	Corn/grass	Dry-lot truck removal	Liquid broadcast 1-wk incorporation	10,323	86
Texas (Central)	723	1,000	0	Freestall	800	Sorghum/grass	Scrape, solid separation, earthen basin	Liquid broadcast 1-wk incorporation	10,023	86
Minnesota	638	5,500	0	Freestall	3,035	Corn/alfalfa/soybean	Digester, solid separation, lagoon	Injection	9,534	28
Wisconsin	637	150	115	Freestall	132	Corn/alfalfa	No storage	Broadcast, no incorporation	9,929	17
New York	877	1,260	925	Freestall	983	Corn/wheat/alfalfa and grass	Scrape, digester, solid separation, earthen basin	Broadcast, 2-d incorporation	10,271	44
Pennsylvania	877	1,000	780	Freestall	832	Corn/wheat/alfalfa and grass	Flush, solid separation, earthen basin	Broadcast, 2-d incorporation	11,251	13
Pennsylvania	1,012	100	76	Grazing, freestall	101	Corn/alfalfa and grass	Barn scraper, open slurry tank	Broadcast, 2-d incorporation	8,400	21

Table A2. Comparison of model predicted annual environmental impacts to measured or empirical values

	Confinement/dry-lot farms		Grazing farms	
Environmental impact category	Simulated	Measured	Simulated	Measured
N volatilized (kg of N/ha)	44.5–1,092	NMF[1]	44.5	7–186[2]
Nitrous oxide farmland (kg of N_2O/ha)	0.9–10.8	3.22–17.86[3]	6.24	2.37–4.3[3]
Total P runoff (kg of P/ha)	0–2.4	0.7–10.6[4]	1.1	0.007–13[2]
Nitrogen leached (kg/ha)	7.1–106.4	29–117[5]	21.3	NMF
N runoff (kg of N/ha)	0.1–10.9	1.2–52.8[4]	1.9	0.1–1.5[4]

[1]No measurement found.

[2]Belflower et al. (2012).

[3]Lazcano et al. (2016).

[4]Harmel et al. (2009).

[5]Toth et al. (2006).

Table A3. Farm profitability, N fertilizer expenses, and environmental N losses

Size, annual cost, and income			N fertilizer cost		N losses (kg/ha)				
State	No. of milk cows	Total cost ($/t of milk)	Fertilizer N (kg/ha)	Cost of N fertilizer ($/t of milk)	Volatilized	Leached	Denitrified	Runoff	Cost reduction commercial N elimination (%)
California	2,000	302.68	200	3.245	425	12	236	4.5	1.1
Idaho	280	418.61	86	6.067	132	7	55	0.8	1.4
Idaho	7,000	314.95	63	2.748	125	35	56	0.1	0.9
Texas (West)	3,222	340.60	124	8.946	473	21	221	4.0	2.6
Texas (Central)	1,000	404.54	138	19.796	69	21	38	0.9	4.9
Minnesota	5,500	267.88	169	2.253	28	111	24	1.2	0.8
Wisconsin	150	348.43	38	2.911	42	54	7	1.2	0.8
New York	1,260	245.52	16	0.963	62	49	13	0.9	0.4
Pennsylvania	1,000	253.00	17	1.087	64	19	41	7.4	0.4
Pennsylvania	100	340.30	36	3.742	45	21	20	1.9	1.1