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Key nitrogen and phosphorus performance indicators derived from farm-gate mass balances on dairies

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ABSTRACT

Efficient management of N and P on dairy farms is critical for farm profitability and environmental stewardship. Annual farm-gate nutrient mass balance (NMB) assessments can be used to determine the nutrient-use efficiency of farms, set efficiency targets, and monitor the effect of management changes with minimal inputs required. In New York, feasible N and P balances have been developed as benchmarks for dairy farm NMB, alongside key performance indicators (KPI) that serve as predictors for high NMB. Here, 3 yr of NMB data from 47 farms were used to evaluate the main drivers of N and P balances and identify additional KPI. From the 141 farm records, 26% met both the feasible N balances per hectare and per megagram of milk produced. For P, 53% of the records met both benchmarks. Imports, rather than exports, drove NMB primarily by feed and fertilizer purchases, consistent with earlier findings. Linear regression analysis showed that a selection of KPI currently used, particularly animal density, nutrient-use efficiency, and the amount of home-grown feed, explained a large portion of variation in NMB. Heifer-to-cow ratio and the relative proportion of various forage crops may provide further insight into the drivers of feed and fertilizer imports and ultimately farm-gate NMB. This study provides avenues toward a better assessment of whole-farm nutrient management and means for farms to communicate progress to stakeholders and consumers.

Key words: whole-farm assessment, nutrient management, mass balance, KPI

INTRODUCTION

Dairy farming is integral to many economies worldwide. In the United States, milk is produced in all 50 states. However, 54% of all milk produced in the United States comes from dairies in California, Wisconsin, Idaho, Texas, and New York (USDA-ERS, 2022). Independent of the location of the farm, efficient management of nutrients such as N and P is critical for both farm profitability and environmental stewardship. Sufficiency in crop-available soil N and P throughout the growing season is essential for attaining high yield and quality of feed to meet herd requirements. However, N and P can be lost from agricultural systems, which can result in unfavorable environmental effects, such as eutrophication of aquatic systems (Correll, 1998; Scavia et al., 2014) or global warming (Butterbach-Bahl et al., 2013; Ussiri and Lal, 2013).

Nutrient balancing approaches are relatively simple to conduct, yet generate useful information to gain insight into the nutrientuse efficiencies of dairy farming systems on a field, farm, or landscape scale (Öborn et al., 2003; Oenema et al., 2003). Defined as the difference between imported and exported nutrients, balances can be used to monitor farm progress, track nutrient utilization in individual fields, find potential for improving nutrient management, and guide future farm management decisions (Fangueiro et al., 2008; Gourley et al., 2012; Ruane et al., 2014; Cela et al., 2015; Mihailescu et al., 2015). For whole-farm systems, these farm-gate balance approaches often do not include the measurements or estimations of individual nutrient losses, such as ammonia volatilization or P runoff from the farm, but instead estimate a balance that includes these losses by tallying nutrients that enter or leave via the farm-gate via imports or exports. This approach keeps the required information to conduct these balances to a minimum and avoids the necessity of, and uncertainty associated with, deriving loss factors. Over the past 2 decades, farm-gate nutrient mass balances (**NMB**) have been calculated and applied throughout the United States. Examples of states for which NMB have been reported include New York (Cela et al., 2014), Pennsylvania, and Vermont in the northeastern United States (Anderson and Magdoff, 2000), Idaho and Utah in the western United States (Spears et al., 2003a,b; Hristov et al., 2006), Nebraska in the Midwest

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(Koelsch, 2005), and Virginia in the Mid-Atlantic region (Pearce and Maguire, 2020).

Dairy farming is the dominant use of agricultural land in the northeastern United States. For example, the 2019–2020 USDA Agricultural Statistics Annual Bulletin for New York estimated 625,000 milking cows, 627,000 ha of hay or haylage (which comprises crops such as grass, grass-legume mixtures, alfalfa, grass-alfalfa mixtures, and small grains), and 425,000 ha of corn, resulting in New York being the fourth-largest milk-producing state in the United States (USDA-NASS, 2020, 2021a). Vermont, with 120,000 milking cows, 111,000 ha of hay or haylage, and 34,000 ha of corn, also has a significant dairy industry (USDA-NASS, 2021b). Dairy farms range in size and animal density across the region, yet many farms have sufficient land to grow all forage required by the herd on their own land base. The farm-grown forages consist predominantly of corn silage, haylage of grass or grass-alfalfa mixtures, and pasture, and to a lesser extent of other forms of haylage, hay, and small grains. In New York, home-grown forage represents 60–70% of the total ration (Cela et al., 2014).

Phosphorus management on New York dairy farms has undergone significant changes over the past 2 decades. Fertilizer P imports and feed P concentrations have decreased in New York following the introduction of comprehensive nutrient management plans for concentrated animal feeding operations, the first New York P runoff index (Czymmek et al., 2003), an active on-farm research network to evaluate the need for fertilizer P (Ketterings et al., 2005, 2011), reduction in P use in animal rations (Cerosaletti et al., 2004), and NMB assessments. As a result, farm-gate P surpluses have, in general, declined over time (Ketterings and Czymmek, 2012; Cela et al., 2015, 2016, 2017; Soberon et al., 2015).

To guide nutrient management practices, NMB have been included in the adaptive management policy for concentrated animal feeding operations in New York (Nutrient Management Spear Program et al., 2018). Benchmarks were established for N, P, and potassium, based on NMB of 102 dairy farms in 2006 to serve as achievable sustainability and efficiency targets for dairy farms (Cela et al., 2014). The New York benchmarks, referred to as feasible NMB, are expressed as an optimal balance range for cropland sustainability (the balance per unit of land base area) and an optimal range for milk production efficiency (the balance per unit of milk exported); farms that meet both targets are said to operate within the optimal operational zone or Green Box (Ros et al., 2018). Farms that operate within this Green Box limit their environmental footprint while ensuring efficient milk production. As farms that participate in annual NMB assessments tend to improve their NMB over time (Cela et al., 2014, 2015; Soberon et al., 2015), New York policy now incentivizes NMB assessment: farms that meet the NMB benchmarks for the balance per unit of land (based on a 3-yr running average) are allowed greater flexibility in land-based nutrient allocation (Nutrient Management Spear Program et al., 2018; Czymmek et al., 2020).

Farms with a NMB outside the Green Box may have opportunities for improvement. However, the NMB values themselves do not indicate what management changes may have the greatest effect on the NMB. Key performance indicators (**KPI**) relating to NMB are needed to identify opportunities to improve nutrient management. Examples of farm characteristics that can serve as KPI are the amount of nutrients imported through feed or fertilizer purchases, the animal density of a farm, the amount of home-grown feed, or the nutrient concentration in feed (Cela et al., 2015; Soberon et al., 2015; Quemada et al., 2020). Such KPI can also be used to monitor and communicate progress. Several KPI, including those listed above, have been evaluated and shared with farms participating in the New York NMB assessment (Cela et al., 2015; Soberon et al., 2015; Ros et al., 2018), but there is an increasing demand for additional KPI to help identify further opportunities to improve NMB. In this study, we use 3 consecutive years of data from 47 dairy farms to evaluate the main drivers for farm-gate N and P mass balances, confirm the importance of existing KPI, and identify new potential KPI.

MATERIALS AND METHODS

Because no human or animal subjects were used, this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

Data Collection

The process of NMB data collection has been described in detail in earlier studies conducted in New York (Soberon et al., 2013; Cela et al., 2014). To summarize, farmers in the northeastern region of the United States were approached directly or indirectly (e.g., through farm advisors) to participate in the NMB project. To gather the data necessary to calculate the NMB, farmers were asked to supply farm information and records on farm size, land area, animals on the farm, crops grown, and commodities imported and exported in the last calendar year. A comprehensive list

Table 1. Descriptive statistics of selected farm characteristics for the 47 dairy farms in the database[1]

Characteristic	All farm records (n = 141)						
	Mean	SD	Min	Q1	Med	Q3	Max
Farm size							
Milk cows (n)	577	639	48	129	330	765	3,296
Animal units[2] (AU)	1,114	1,278	73	227	603	1,579	6,262
Tillable land (ha)	475	471	46	111	295	657	2,337
Land with legumes[3] (%)	35	24	0	11	42	53	90
Herd management							
Milk exported (Mg cow^{-1} yr^{-1})	10.6	1.6	6.7	9.5	10.6	11.7	14.1
Home-grown feed (% of total feed)	71	8	50	66	72	76	87
Home-grown forage (% of total feed)	69	9	40	64	69	75	87
CP in ration (%)	15.4	1.54	10.9	14.5	15.6	16.3	20.4
P in ration (%)	0.36	0.05	0.24	0.33	0.35	0.38	0.56
Density							
Animal density (AU ha^{-1})	2.12	0.58	0.90	1.77	2.10	2.50	3.73
Milk sold (Mg ha^{-1})	12.0	4.1	4.5	9.0	11.6	14.8	23.2

[1]Min = minimum; Q1 = first quartile; Med = median; Q3 = third quartile; Max = maximum.

[2]One animal unit = 454 kg (1,000 lbs) of animal weight (cows, heifers, calves).

[3]Land with legumes = cropland with at least 10% of legumes.

of data supplied can be found in Soberon et al. (2013). Data were acquired primarily through the farmers' field management records and laboratory analyses of crops, milk, and manure to obtain N and P content. If recent and reliable records or analyses were lacking, software default values from the Cornell University NMB Calculator (Soberon et al., 2013), long-term average estimates from the Dairy One feed library (Dairy One, 2021), and expert knowledge from farmers and their farm advisors were used to complete the input forms. On completion of the assessment, farmers received a report that included their annual NMB and associated KPI, their NMB trends over time, and a comparison to their peers.

For the current analysis, only farms with 3 consecutive completed balances for the years 2016, 2017, and 2018 were included. To ensure data quality, farms with large changes (more than 25%) in the amount of land used or animals kept from one year to the next were excluded, unless the change was consistent over the 3 yr, showing a gradual expansion or downsizing of the farm operation. Farms whose data showed exceptional deviation from common dairy farming practice (e.g., an uncharacteristically low milk yield or the absence of farm-produced feed altogether) were considered outliers and excluded from further analysis. Records for 2 farms with Jersey cows were excluded from the analyses as well as Jersey cows tend to have lower BW, lower milk yields, and a higher milk protein content than the predominant Holstein breed of the database. This resulted in a total of 47 farm records being available for the analysis.

Database Characteristics

Over the 3 recorded years, farms in the database had a mean herd size of 567 cows (lactating and dry) and 468 ha of tillable land (land that can be used to produce crops; Table 1). The median farm size was 330 cows and 295 tillable ha, resulting in a median animal density of just over 2 animal units (**AU**) ha^{-1} (1 AU = 454 kg or 1,000 lbs of animal weight). Most of the farm data related to size and intensity were positively skewed, with a relatively small number of very large farms. On average, one-third of the tillable land had a plant stand with 10% legumes or more. Milk production per cow varied from 6.7 to 14.1 Mg cow^{-1} yr^{-1} and averaged around 10.6 Mg cow^{-1} yr^{-1}, which corresponded to a milk production of 4.1 to 23.2 Mg ha^{-1} and an average of 12.0 Mg ha^{-1}. The farms in the database produced an average of 71% of the total feed on-farm (ranging from 50 to 87%, on a DM basis), almost all of which was forage, mostly consisting of corn silage, grazed pasture, various forms of haylage (grass, grass mixtures, alfalfa), and hay. Crude protein and P concentrations in the total feed diet varied significantly among farms, with an average of 15.4% CP and 0.36% P.

Calculations

Farm-gate NMB for N and P were calculated using the Cornell University NMB Calculator (Soberon et al., 2013). For each farm, NMB were obtained by subtracting the total N and P in exported milk (recorded as shipped milk), animals, crops, and other products

Table 2. Descriptive statistics of the farm characteristics currently used as indicators to predict a high risk of exceeding feasible nitrogen (N) and phosphorus (P) balances for the 47 dairy farms in the database[1]

	All farm records (n = 141)						
Farm characteristic	Mean	SD	Min	Q1	Med	Q3	Max
Milk per cow (Mg cow^{-1} yr^{-1})	10.6	1.6	6.7	9.5	10.6	11.6	14.1
Animal density (AU ha^{-1})	2.12	0.58	0.90	1.77	2.10	2.50	3.73
Whole-farm NUE (%)	44	27	15	32	37	45	265
Whole-farm PUE (%)	61	26	23	47	55	66	232
Feed N imports (kg ha^{-1})	137	61	30	98	124	170	316
Feed P imports (kg ha^{-1})	20.3	9.0	4.7	14.5	18.7	24.5	46.8
Feed (Mg of DM AU^{-1})	6.4	1.3	3.1	5.4	6.2	7.2	10.1
N feed use efficiency (%)	20	4	10	17	19	22	36
P feed use efficiency (%)	23	5	12	20	23	27	46
Home-grown feed (%)	71	8	50	66	72	76	87
Home-grown CP (%)	58	11	32	50	59	65	82
Home-grown P (%)	57	11	34	50	59	64	83
CP in all feed (%)	15.4	1.5	10.9	14.5	15.6	16.3	20.4
P in all feed (%)	0.36	0.05	0.24	0.33	0.35	0.38	0.56
CP in purchased feed (%)	22.1	3.7	14.3	19.9	22.2	24.2	36.5
P in purchased feed (%)	0.52	0.10	0.23	0.47	0.52	0.58	0.85
CP in home-grown feed (%)	12.6	1.7	9.0	11.4	12.3	13.7	18.1
Fertilizer N imports (kg ha^{-1})	64	41	0	31	63	87	183
Fertilizer P imports (kg ha^{-1})	4.3	4.3	0.0	1.1	3.2	6.2	26.2
Crop N exports (kg ha^{-1})	5.9	12.1	0.0	0.0	0.0	5.5	62.8
Crop P exports (kg ha^{-1})	0.76	1.50	0.00	0.00	0.00	0.76	7.28
Manure N exports (kg ha^{-1})	3.9	14.1	0.0	0.0	0.0	0.3	127.0
Manure P exports (kg ha^{-1})	0.88	2.39	0.00	0.00	0.00	0.15	16.98

[1]Min = minimum; Q1 = first quartile; Med = median; Q3 = third quartile; Max = maximum. AU = animal unit = 454 kg (1,000 lbs) of animal weight (cows, heifers, calves). NUE = nitrogen use efficiency; PUE = phosphorus use efficiency (exported nutrients/imported nutrients × 100%).

(mostly manure) from total N and P imported through feed, fertilizers, animals, and other items (mostly bedding). Balances were subsequently expressed per tillable hectare as the indicator of the farm's ability to recycle nutrients on its own land base and per megagram of milk exported as the milk nutrient use efficiency indicator. Additional farm characteristics that are commonly used as KPI (Table 1 and Table 2) were calculated according to Cela et al. (2014, 2015) and Soberon et al. (2015). As approximately all farms produced their herd's forage needs on the farm itself and relied on feed imports mainly for supplementary and concentrate feed, home-grown feed and home-grown forage relative to the total amount of feed required were very similar (Table 1). We therefore only included home-grown feed in our KPI analyses.

Additional characteristics, beyond those identified by Cela et al. (2014, 2015) and Soberon et al. (2015) and currently shared with participating farmers, were derived from the data and evaluated as potential KPI of high NMB (Table 3 and Table 4), which are NMB that exceed the feasible limits set by Cela et al. (2014). Average total crop DM yield per hectare and individual DM yields for the 3 main forage crops (corn silage, haylage, and pasture) were included, in addition to relative tillable area, relative DM yield, and relative contribution of crops to total N and P harvested from cropland on the farm. For data relating to yields and nutrient contents of pastureland, a combination of software default values and expert judgment (grass contents of 9% CP and 0.27% P; see also Table 4) were often relied upon due to the lack of reliable crop analysis data. Therefore, only corn silage and haylage DM yield and nutrient content data were used in the KPI analyses; pasture-related nutrient composition characteristics could not be assessed with sufficient precision. For terms such as forage, haylage, and hay, the definitions set by the USDA were used as a guideline (USDA-NASS, 2019). Whole-farm feed conversion was calculated by dividing the amount of feed on a DM basis (corrected for inventory changes) by the amount of milk exported. The heifer to cow ratio was calculated based on AU (454 kg or 1,000 lbs of animal weight), rather than on number of animals. Nutrient mass balances were determined, with and without manure exports included, to more clearly evaluate the effect of management decisions related to major imports (feed and fertilizer) without potential influence of nutrient exports with manure.

Simple Linear Regression of Explanatory Variables

Relationships between N and P imports, exports (including manure if the farm listed manure exports), and NMB were investigated using linear mixed ef-

Table 3. Relationships between the existing key performance indicators (KPI) and farm-gate nitrogen (N) and phosphorus (P) balances as well as the corresponding threshold values determined in previous studies and by the current study, the 2 coefficients of variation of the model, and the *P*-value for the equation coefficient[1]

KPI	Existing threshold	Calculated threshold (x)	Relationship equation	R^2m	R^2c	*P*-value coefficient
y = N balance (kg ha^{-1})						
Animal density (AU ha^{-1})	—	>1.95	y = 65.12x − 8.89	0.341	0.640	<0.001
Whole-farm NUE (%)	<44	<41	y = −152.7ln(x) + 685.3	0.566	0.906	<0.001
Feed N imports (kg ha^{-1})	>136	>126	y = 0.949x − 1.46	0.627	0.861	<0.001
Fertilizer N imports (kg ha^{-1})	>44	>55	y = 1.28x + 47.25	0.560	0.891	<0.001
Home-grown feed (%)	<65	<74	y = −3.37x + 366.78	0.190	0.691	<0.001
Home-grown forage (%)	—	<73	y = −2.57x + 305.44	0.114	0.718	<0.001
Home-grown N (%)	<50	<62	y = −3.07x + 308.30	0.282	0.663	<0.001
CP in all feed (%)	>17	>14	y = 11.14x − 42.44	0.072	0.632	<0.001
y = N balance (kg Mg^{-1} milk exported)						
Whole-farm NUE (%)		<43	y = −14.16ln(x) + 62.20	0.876	0.930	<0.001
Feed N imports (kg ha^{-1})		>96	y = 0.0435x + 4.64	0.236	0.686	<0.001
Fertilizer N imports (kg ha^{-1})		>45	y = 0.0953x + 4.54	0.581	0.785	<0.001
N feed use efficiency (%)		<24	y = −8.29ln(x) + 35.09	0.130	0.591	<0.001
Home-grown feed (%)		<82	y = −0.166x + 22.33	0.080	0.532	<0.001
Home-grown N (%)		<71	y = −0.141x + 18.86	0.114	0.540	<0.001
y = P balance (kg ha^{-1})						
Animal density (AU ha^{-1})	>2.47	>2.21	y = 7.749x − 4.123	0.277	0.707	<0.001
Whole-farm PUE (%)	<51	<52	y = −21.3ln(x) + 97.2	0.575	0.925	<0.001
Feed P imports (kg ha^{-1})	>22	>21	y = 0.812x − 4.157	0.676	0.877	<0.001
Fertilizer P imports (kg ha^{-1})	>7	>5	y = 0.872x + 8.505	0.194	0.732	<0.001
Home-grown feed (%)	<65	<69	y = −0.418x + 41.76	0.189	0.673	<0.001
Home-grown forage (%)	—	<66	y = −0.318x + 34.10	0.113	0.706	<0.001
Home-grown P (%)	<50	<56	y = −0.450x + 38.14	0.352	0.758	<0.001
P in purchased feed (%)	>0.60	>0.55	y = 26.53x − 1.59	0.094	0.696	<0.001
y = P balance (kg Mg^{-1} milk exported)						
Whole-farm PUE (%)		<52	y = −1.97ln(x) + 8.87	0.925	0.950	<0.001
Feed P imports (kg ha^{-1})		>22	y = 0.0490x + 0.015	0.367	0.809	<0.001
Fertilizer P imports (kg ha^{-1})		>6	y = 0.0623x + 0.736	0.192	0.584	<0.001
P feed use efficiency (%)		<21	y = −0.904ln(x) + 3.833	0.110	0.592	<0.001
Home-grown feed (%)		<66	y = −0.0218x + 2.54	0.090	0.559	<0.001
Home-grown P (%)		<54	y = −0.0303x + 2.75	0.253	0.707	<0.001
P in purchased feed (%)		>0.56	y = 2.321x − 0.208	0.166	0.608	<0.001

[1]Current thresholds are based on (Cela et al., 2014; Soberon et al., 2015; Ros et al., 2018). R^2m = adjusted marginal coefficient of variation; R^2c = conditional coefficient of variation. AU = animal unit = 454 kg (1,000 lbs) of animal weight (cows, heifers, calves). NUE = nitrogen use efficiency; PUE = phosphorus use efficiency (exported nutrients/imported nutrients × 100%).

fects models to identify the main imports (i.e., feed, fertilizer, animals, bedding) and exports (milk, crops, animals, and manure) that drive NMB. Subsequently, linear regression was performed to identify explanatory variables (potential KPI) that model the relationship between NMB without manure exports and individual farm and management characteristics (such as animal density, and CP and P in the diet, respectively). These variables are referred to as first-tier indicators. The resulting relationships were used to (1) generate threshold values for individual farm characteristics that indicate a higher risk of exceeding feasible NMB limits, and (2) assess the suitability of these individual farm characteristics as potential indicators of high N and P balances expressed per hectare or per megagram of milk exported.

The linear mixed effects models were fitted by restricted maximum likelihood using the R statistical software "lme4" package (Bates et al., 2015) with NMB result as the dependent variable. Farm name and year were included as random effects to account for repeated measures of farms (farm name) and between year variation beyond the farmers' control [e.g., weather (year)]. The individual farm and management characteristics were included as fixed effects and analyzed one at a time for their relationship with the NMB. When the relationship between the whole-farm NMB and KPI was clearly nonlinear, as determined from visual evaluation, the indicator was transformed using the natural logarithm. This transformation was necessary for the whole-farm nutrient-use efficiency indicators. For each model, the adjusted coefficient of multiple determina-

Table 4. Descriptive statistics of potential new key performance indicators (KPI) to predict a high risk of exceeding feasible nitrogen (N) and phosphorus (P) balances for the 47 dairy farms[1]

	All farm records (n = 141)						
Farm characteristic	Mean	SD	Min	Q1	Med	Q3	Max
Average crop yield (Mg of DM ha^{-1})	9.47	2.19	4.37	7.77	9.35	10.9	16.4
Corn silage yield (Mg of DM ha^{-1})	13.5	5.21	0	12.2	14.1	17.2	22.5
Haylage yield (Mg of DM ha^{-1})	7.47	2.29	2.29	6.28	7.49	8.97	14.5
Pasture yield (Mg of DM ha^{-1})	3.41	2.98	0	0	4.48	5.60	8.97
Relative corn silage yield[2] (%)	53.7	20.2	0	49.2	57.5	64.5	85.8
Relative haylage yield (%)	31.9	10.9	12.7	25.8	30.8	35.5	60.0
Relative pasture yield[3] (%)	14.4	14.5	0	0	16.8	21.9	64.9
Corn silage CP concentration[4] (%)	7.8	0.94	6.0	7.2	7.6	8.1	13.0
Haylage CP concentration (%)	18.4	2.22	9.8	17.6	18.5	19.9	22.8
Corn silage P concentration (%)	0.23	0.028	0.16	0.21	0.23	0.25	0.32
Haylage P concentration (%)	0.34	0.065	0.18	0.31	0.35	0.37	0.81
Relative corn silage N yield (%)	29.7	15.4	0	21.2	30.4	38.4	78.4
Relative haylage N yield (%)	65.1	13.7	21.6	58.4	65.9	72.1	96.2
Relative pasture N yield (%)	5.23	7.94	0	0	1.96	8.04	57.8
Relative corn silage P yield (%)	38.8	19.5	0	28.2	40.9	51.8	85.5
Relative haylage P yield (%)	54.4	16.4	14.5	44.0	55.1	65.5	95.4
Relative pasture P yield (%)	6.80	9.97	0	0	2.74	12.0	69.1
Corn silage tillable area (%)	31.4	16.1	0	20.6	34.1	43.6	64.5
Haylage tillable area (%)	58.6	12.3	32.3	49.8	57.5	66.7	90.3
Pasture tillable area (%)	10.0	12.1	0	0	5.7	18.6	63.5
Feed conversion (kg of DM kg^{-1} milk)	0.924	0.236	0.435	0.768	0.904	1.07	1.96
Heifer:cow ratio	0.745	0.272	0	0.60	0.79	0.92	1.45
Cow weight (kg)	637	36.4	544	612	635	658	748
Milk CP (%)	3.11	0.079	2.90	3.08	3.10	3.15	3.34

[1]Min = minimum; Q1 = first quartile; Med = median; Q3 = third quartile; Max = maximum.

[2]Relative areas and yields of forage crops (corn silage, haylage, and pasture) are calculated as a percentage of total forage crops on the farm.

[3]Due to lack of data, pasture was assumed to have average CP and P concentrations of 9% and 0.27%, respectively, but nutrient concentrations of pasture were not considered as potential indicators.

[4]Descriptive statistics for CP and P concentrations in corn silage are based only on the 127 records for which corn silage is reported.

tion, R^2, for the fixed effects (the marginal R^2, or R^2m) and the model as a whole (the conditional R^2, or R^2c; (Nakagawa and Schielzeth, 2013), were calculated using the r.squared.GLMM() function of the R package “MuMIn” to provide an absolute value for the goodness-of-fit. The conditional R^2 is a measure of the variance in the dependent variable explained by the model as a whole (both fixed and random effects), whereas the marginal R^2 is a measure of the variance explained by the fixed effects alone:

$$\text{Adjusted } R^2m = 1 - (1 - R^2m) \times [(n - p)/(n - p - 1)]$$

and

$$\text{Adjusted } R^2c = 1 - (1 - R^2c) \times [(n - p)/(n - p - 1)],$$

where n is the number of observations used to construct the model; p is the number of parameters in the model; R^2m is the marginal R^2 (for the fixed effects only), and R^2c is the conditional R^2 (for the model as a whole).

A farm or management characteristic (Tables 2 and 4) was considered as a potential KPI if we detected a significant relationship between the farm-gate N or P balance and the individual farm characteristic ($P < 0.05$), and if the marginal R^2m (i.e., the part of uncertainty that is explained by the fixed factors) was equal to or greater than 0.05. An indicative threshold value was then generated by substituting the feasible balance limits previously determined (Cela et al., 2014) into the newly derived equation:

$$\text{Indicative threshold value} = (\text{feasible balance} - c)/m,$$

where m is the coefficient and c is the intercept determined through fitting of the described linear mixed effect model.

Relationships between individual N and P feed and fertilizer imports and potential second-tier KPI (secondary indicators; Table 4) were determined using the same methodology as the first-tier KPI, with the exception that the N and P feed and fertilizer imports were the dependent variable, and threshold values determined for feed and fertilizer imports were substituted one at a time into the respective derived equations to determine thresholds for these secondary indicators. Manure exports were not excluded from the fertilizer import model as manure export could influence the need for fertilizer imports.

Multiple Linear Regression Models

In addition to the assessment of individual farm and management characteristics as indicators, the predictive value of combinations of KPI was explored using linear mixed effects models. As the scales of the different KPI (fixed effects) varied substantially, they were transformed to reduce excessive influence of any particular KPI due to dimensional effects (Frey and Patil, 2002). For the transformation, all KPI were divided by their maximum value, to give new continuous values on a scale from zero to one.

Separate minimal linear mixed effects models were fitted by restricted maximum likelihood using the R "lme4" package (Bates et al., 2015) with the N balance per hectare and the P balance per hectare as dependent variables. First, the transformed KPI (or farm management characteristics; Table 2) were included as fixed effects to fit the full model. Second, backward step-wise removal of least significant fixed effects (KPI) to find the minimal model was performed using the R "stats" package. At each step, the performance of the resulting reduced model was determined using the second-order Akaike information criterion, which adjusts Akaike information criterion for small samples sizes. The use of Akaike information criterion is equivalent to performing the leave-one-out-cross-validation method, and avoids the need to exclude data for model validation at a later stage (Fang, 2011). In addition, the residuals of the reduced models were assessed for normality using histograms and Q-Q plots. If normal, the model was compared with the null model and the model from the previous step. The reduced model was retained if we observed a significant ($P < 0.05$) change in deviance from the null model, and a nonsignificant ($P \geq 0.05$) change in deviance from the previous model. Change in deviance was based on log-likelihood estimates: a chi-squared value equaling twice the difference between the log-likelihood of the 2 nested models and the degrees of freedom for the chi-squared distribution were taken. Marginal and conditional R^2 were calculated for the final minimal models, using the R package "MuMIn" to provide an absolute value for the goodness-of-fit.

The full models with N balance per hectare and P balance per hectare as dependent variables were refitted including both the farm and management characteristics that are currently used as KPI (Table 2) and all of the potential new KPI (Table 4) as fixed effects. Backward step-wise removal of least significant fixed effects (KPI) was used to find the minimal model and the reduced and minimal models were assessed as previously described.

Whole-farm nutrient-use efficiency (NUE for N and PUE for P) was not included as a fixed effect (potential KPI) because it is an alternative representation or calculation of the NMB (NMB = imports − exports, NUE or PUE = exports/imports) and we detected a strong correlation between the 2 (Table 3). Feed use efficiency was also excluded as potential KPI because it is calculated from other feed- and milk-related KPI (e.g., milk production, nutrient concentrations in all feed) which are already included in the full model. These KPI used to derive feed-use efficiency were chosen over feed-use efficiency itself as they provide more tangible opportunities for management change. The remaining potential fixed effects were assessed for collinearity using variance inflation factor with a threshold of 10. This identified collinearity between home-grown feed, home-grown forage, and home-grown grain, and therefore only the home-grown feed KPI was included as a potential fixed effect in the models. Although some collinearity was seen between CP in all feed, purchased feed and home-grown feed, both CP in all feed and home-grown feed were retained as potential fixed effects as they are more relatable KPI for farmers and their advisors than CP in home-grown feed or purchased feed alone.

The methodology described above was repeated using feed and fertilizer N and P imports as the dependent variables. This assessment was done to identify potential KPI for the main drivers of NMB, feed, and fertilizer nutrient imports. The KPI identified through these analyses were classified as second-tier indicators.

RESULTS AND DISCUSSION

Variation in N and P Balances

Farm-gate N balances per tillable area ranged from −74 to 363 kg of N ha^{-1} (Figure 1a). A total of 47% of the farm records had N balances below the upper feasible limit (≤118 kg of N ha^{-1}) determined for New York (Cela et al., 2014). The N balances per megagram of milk exported ranged from −14.8 to 33.6 kg of N Mg^{-1} milk, and 35% of the farm records fell below the upper feasible limit per megagram of milk exported (≤8.8 kg of N Mg^{-1}). Of the 141 records, 41 (29%) had balances below the upper feasible limit of N per tillable area as well as per megagram of milk exported. Thirty-six of these (26%) were positive balances (imports > exports) and therefore within the Green Box.

For P, NMB per tillable area ranged from −12 to 42 kg of P ha^{-1} (Figure 1b) and 67% of the farm records had balances below the feasible limit for P (≤13 kg

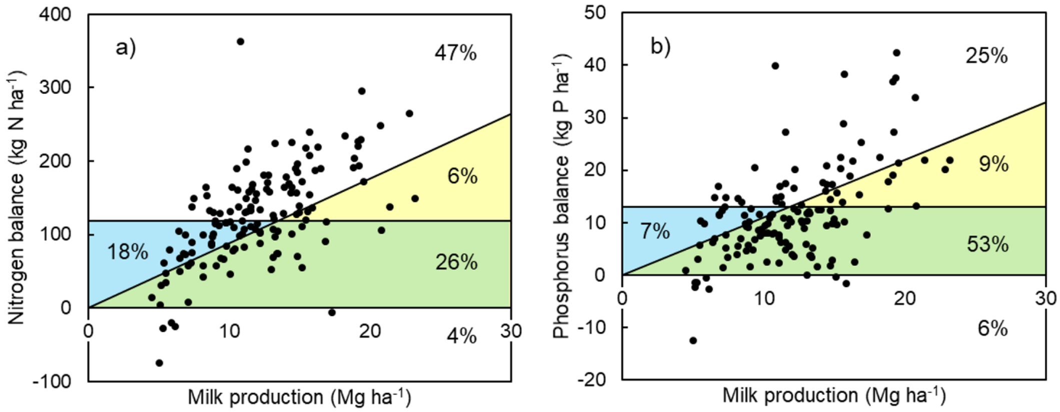

Figure 1. Milk production and farm-gate nutrient mass balances (NMB) for nitrogen (a) and phosphorus (b) of the 47 dairy farms (141 records). The blue area represents NMB records with a feasible balance per tillable area (≤118 kg of N ha^{-1} and ≤13 kg of P ha^{-1}), whereas the yellow area represents NMB records with a feasible balance per megagram of milk exported (≤8.8 kg of N Mg^{-1} and ≤1.1 kg of P Mg^{-1}). Farm records in the Green Box have both feasible balances per tillable area and per megagram of milk exported. The numbers represent the percentage of farm records in each part of the graph.

of P ha^{-1}). The balances per megagram of milk were between −2.5 and 3.7 kg of P Mg^{-1} and 68% of the farm records were below the upper feasible limit per megagram of milk exported (≤1.1 kg of P Mg^{-1}). This corresponded to a total of 85 farm records (60%) meeting both upper feasible limits for P, of which 75 (53%) were in the Green Box.

The difference between the number of records within the Green Box for N versus P reflects, at least in part, that changes are more challenging to implement for N, a nutrient that is easily lost to the environment if not captured. When availability of N is insufficient, it can have a drastic effect on both crop production (Scharf, 2015) and cattle growth and milk production (NASEM, 2021).

Main Drivers of N and P Balances

The NMB showed strong correlation with the total nutrient imports per tillable area for both N and P (R^2 = 0.87 and 0.81 for N and P, respectively; Figure 2). In contrast, total nutrient exports did not correlate well with the NMB (R^2 = 0.10 and 0.08 for N and P, respectively). The relationship with nutrient imports was stronger for NMB expressed per tillable area than per megagram of milk exported. This is to be expected, because the total nutrient imports and exports are also expressed per tillable area. This indicates that a farm's NMB is predominantly determined by nutrient imports; compared with the imports, exports are relatively small and show less variation (Figure 2; Table 2). This was also documented in earlier studies in New York (Cela et al., 2014; Soberon et al., 2015) and elsewhere (Gourley et al., 2012; Quemada et al., 2020).

Feed imports contributed the most to the total imports, followed by fertilizer imports (Figure 3 and 4). On average, farms imported 137 kg of N and 20.3 kg of P per hectare as feed and 64 kg of N and 4.3 kg of P per hectare as fertilizer products (Table 2). The relationship between feed imports and total imports was slightly stronger for P (R^2 = 0.83) than for N (R^2 = 0.74), because feed imports comprised a relatively larger share of the total imports for P than for N; for N, fertilizer imports also played a large role (R^2 = 0.39). Other sources of nutrient imports (animal biomass and miscellaneous items, such as bedding or manure) contributed little to the total amounts, and for many farms these imports were absent altogether.

Milk sales accounted for most of the total variation in N and P exports (R^2 = 0.63 for N and 0.70 for P; Figure 3 and Figure 4). Most of the farms also exported nutrients through animal exports (culled or mortalities exported off the farm). Crop sales or miscellaneous exports (predominantly manure exports) were less common and only incidentally contributed a substantial amount to the total N and P exports. Nevertheless, many of the farms that did report export of P in manure tended to meet the feasible balances per tillable hectare (Figure 4).

These results show that reducing nutrient imports through feed and fertilizer purchases is often the most effective way to reduce both N and P NMB, as was documented previously (Cela et al., 2017). It is, however, important to note that farms with limited area available for manure application, for example higher

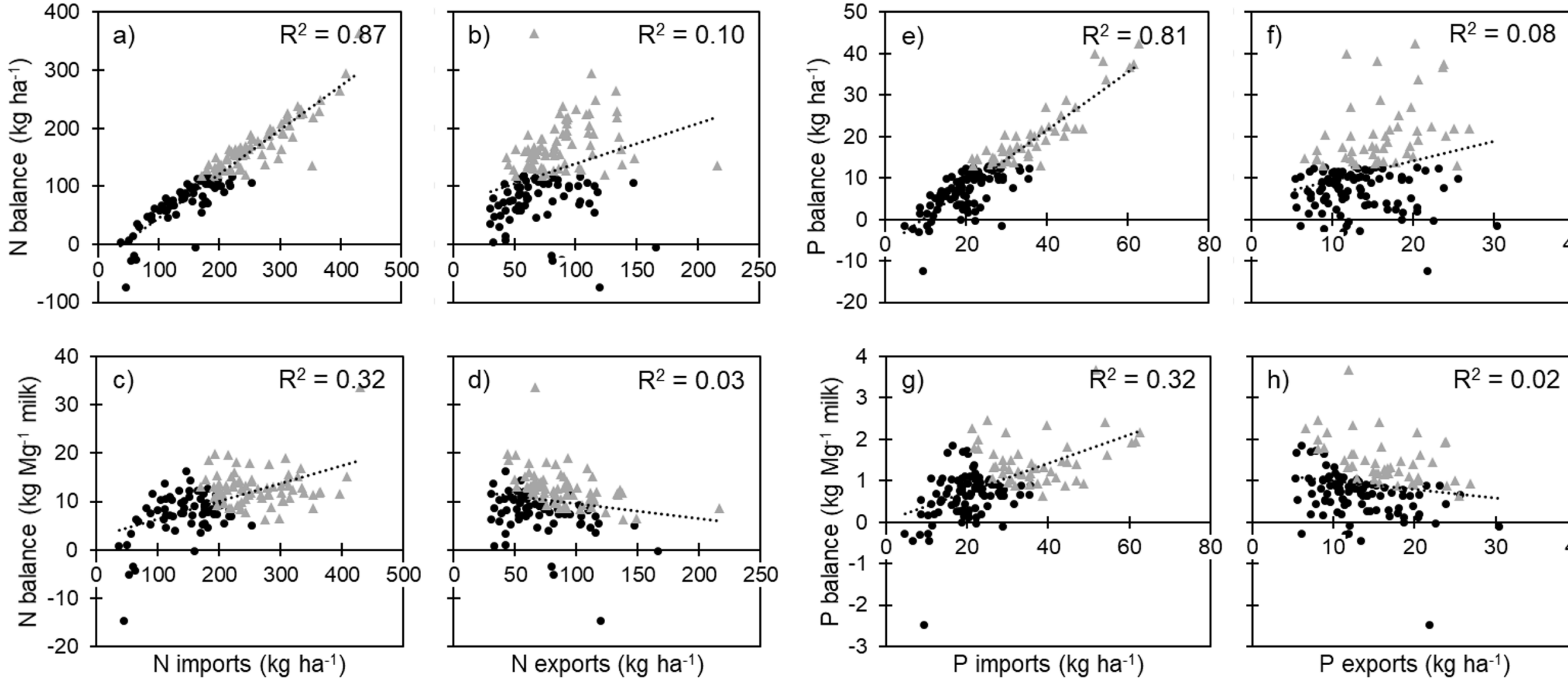

Figure 2. Scatterplots and simple linear regression lines of N (a–d) and P (e–h) balances per tillable area and per megagram of milk exported versus the imports and exports for the 47 dairy farms (141 records) in the database. Black circles represent records that meet the feasible balance threshold per tillable area ($\leq$118 kg of N ha^{-1} or $\leq$13 kg of P ha^{-1}), whereas gray triangles represent records that do not.

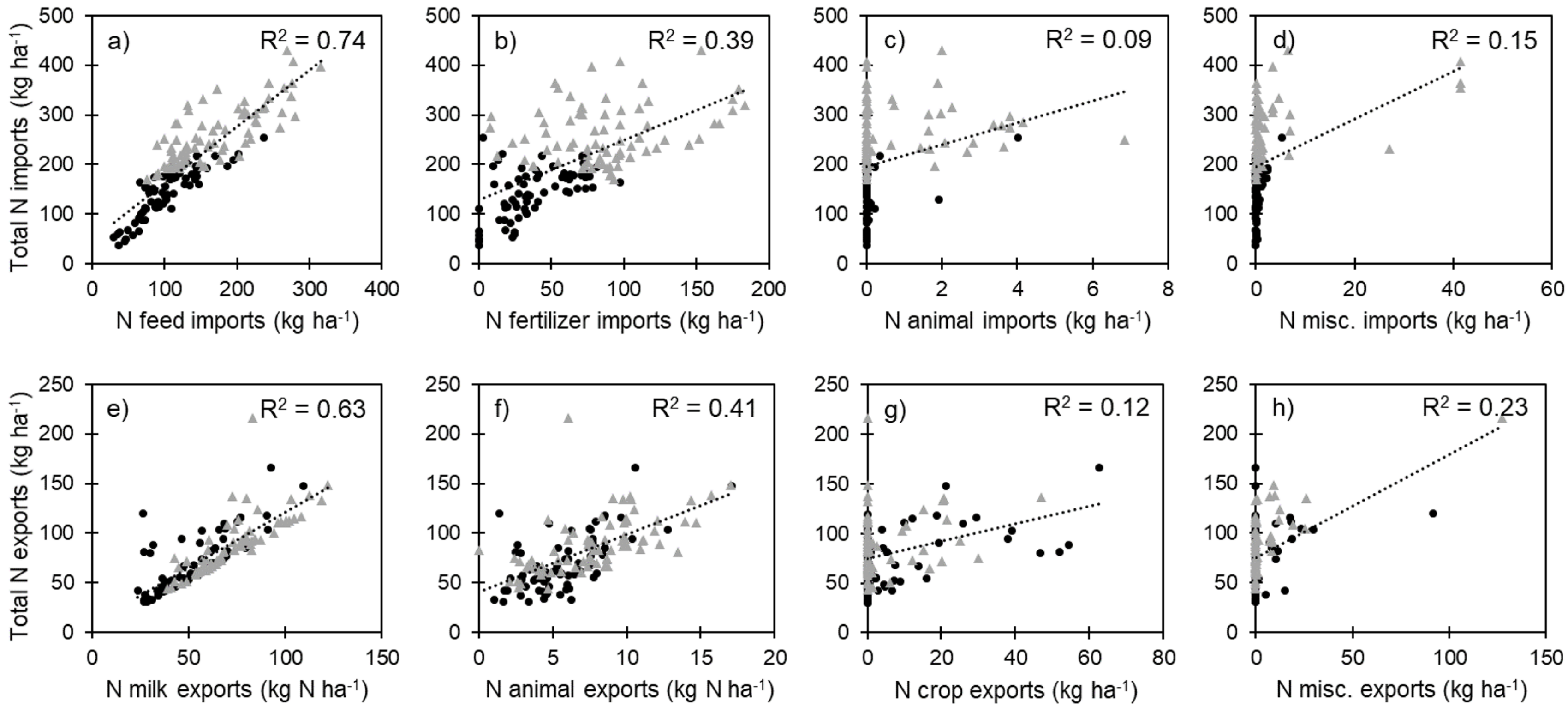

Figure 3. Scatterplots and simple linear regression lines of total N imports (a–d) and exports (e–h) per tillable area versus their individual components for the 47 dairy farms (141 records) in the database. Black circles represent records that meet the feasible balance threshold per tillable area ($\leq$118 kg of N ha^{-1}), whereas gray triangles represent records that do not. Misc. = miscellaneous.

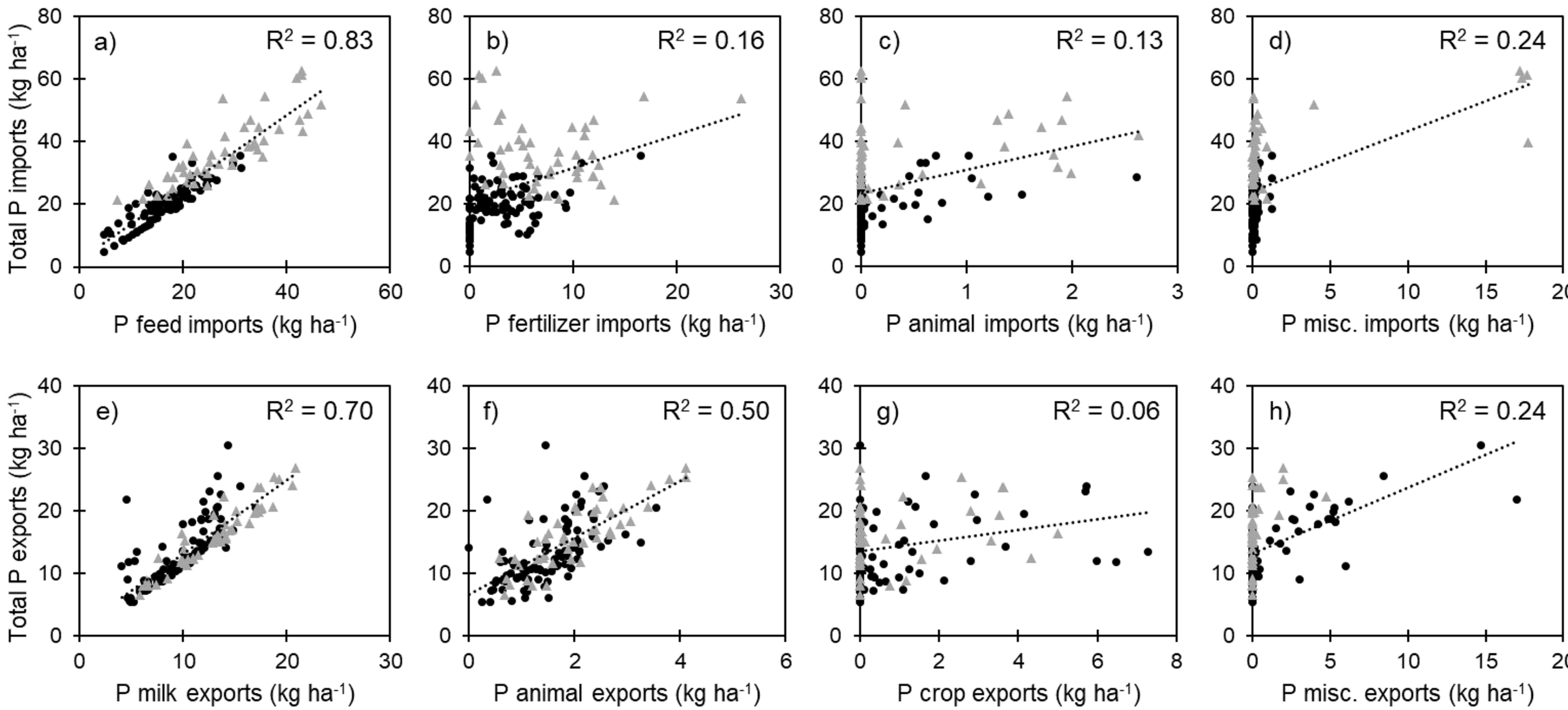

Figure 4. Scatterplots and simple linear regression lines of total P imports (a–d) and exports (e–h) per tillable area versus their individual components for the 47 dairy farms (141 records) in the database. Black circles represent records that meet the feasible balance threshold per tillable area ($\leq$13 kg of P ha^{-1}), whereas gray triangles represent records that do not. Misc. = miscellaneous.

animal density farms, may also lower their NMB by exporting manure (Cela et al., 2014).

Indicators and Threshold Values

The relationships between existing and new variables and farm-gate NMB results were analyzed to identify potential first-tier indicators. When manure exports were removed and the variation between farms and balance years was accounted for, several of the farm and management characteristics currently used as first-tier KPI (KPI that relate directly to the feasible balances per tillable area) for risk of exceeding feasible balances (Table 2) related well to N and P NMB (Table 3). Most notably, nutrient imports through feed and fertilizer purchases, as well as KPI for home-grown feed, showed a strong relationship with the whole-farm NMB. Generally, farms that imported more than 126 kg of N ha^{-1} and 21 kg of P ha^{-1} through feed had a high chance of exceeding the upper limit of the feasible balances for N and P, respectively. For fertilizer, the import thresholds were 55 kg of N ha^{-1} and 5 kg of P ha^{-1}. Thresholds for feed and fertilizer P imports derived for the farms in the current database are similar to those derived in the earlier 2006 data set (Cela et al., 2014; Soberon et al., 2015). For N, the thresholds for overall N imports per tillable area is similar but the distribution between feed and fertilizer shifted to a slightly lower threshold for feed and a slightly higher one for fertilizer. This shift from feed to fertilizer could reflect a difference in whole-farm average crop DM yield between the 2 data sets, reducing the reliance on imported forage (feed imports), but increasing fertilizer imports to achieve the higher home-grown forage yields. This hypothesis is further supported by the fact that farms meeting the feasible N balances in the current database produce a greater proportion of the feed and N (in the form of CP) on-farm than is suggested by the thresholds calculated previously (Cela et al., 2014; Soberon et al., 2015; Table 3).

In addition to nutrient imports through feed and fertilizer purchases, the CP concentration of all feed and the P concentration of purchased feed were identified as useful first-tier KPI for farm NMB, although the predictive power of these relationships was limited (R^2m values <0.13). The relationship between the CP concentration of all feed and the N balance per hectare suggests that farms able to reduce the average CP content of the diet at the farm level (including all animal groups) to 14% have a greater chance of achieving feasible N balances. However, the interaction of the heifer to cow ratio with this KPI was not considered here and warrants further consideration. Earlier studies have shown that maintaining an average diet CP content of 14–15% for lactating dairy cows can be achieved without compromising animal health (Sinclair et al., 2014).

Animal density was another KPI with a relatively high correlation with balances per tillable area (R^2m = 0.34 and 0.28 for N and P balances, respectively). In the original 2006 data set (Cela et al., 2014), the animal density threshold for farms exceeding the feasible P balance per tillable area was higher than the animal density threshold determined in the current data set; thus, farms in the current data set had higher P balances given the same animal density, as farms in the Cela et al. (2014) assessment. This could reflect a disproportionate increase in milk production and corresponding feed intake per cow over time since feasible balances were first derived (2006 data set in Cela et al., 2014). For example, if there is an increase in the amount of P exported in milk per AU, and there is a proportionally greater increase in the amount of P imported in feed per AU, feed efficiency decreases. As a result, the P balance per tillable area will increase, and animal density will need to decrease to stay below the upper limit of the feasible P balance established by Cela et al. (2014). The animal density threshold to meet the N balance per tillable area is lower than the one necessary to meet the P balance per tillable area, which results from a greater proportion of N being lost from manure during storage and after application. This also helps explain why manure exports have a smaller effect on lowering N balances than P balances, particularly as the importance of manure exports on balances increases as animal density increases.

No strong direct relationship between any of the crop production or herd characteristics (potential first-tier indicators, shown in Table 4) and NMB was found. This suggests complexity beyond the percentage of home-grown feed and home-grown forage and highlights the need to evaluate second-tier KPI (KPI relating to specific nutrient imports). Feed imports and fertilizer use are likely affected by crop DM yields and management approaches, such as the outsourcing of heifer raising (heifer-to-cow ratio), despite these variables not being identified as potential first-tier indicators for NMB. Farm characteristics and management practices were also assessed for their potential as second-tier indicators (their relationship with feed and fertilizer nutrient imports). Of the second-tier KPI evaluated for feed imports, those related to home-grown feed had the highest predictive value (Table 5). The corresponding derived thresholds were in line with the thresholds determined by the relationship between these KPI and the NMB (Table 3); farms that produced 62% or more of feed N and 56% or more of feed P on their own land were likely to meet the feasible balances. Relationships between other farm characteristics and nutrient

Table 5. Relationships between key performance indicators (KPI) and nitrogen (N) and phosphorus (P) imported through feed and fertilizer purchases, as well as the corresponding threshold values for exceeding feasible balances, the 2 coefficients of variation of the model, and the *P*-value for the equation coefficient[1]

KPI[2]	Calculated threshold (x)	Relationship equation	R^2m	R^2c	*P*-value coefficient
y = N feed imports (kg ha^{-1})					
Home-grown feed (%)	<74	y = −3.110x + 356.81	0.233	0.856	<0.001
Home-grown forage (%)	<73	y = −2.417x + 303.27	0.136	0.868	<0.001
Home-grown N (%)	<62	y = −3.033x + 314.35	0.407	0.843	<0.001
CP in all feed (%)	>14	y = 9.605x – 10.38	0.067	0.836	<0.001
Pasture yield (Mg of DM ha^{-1})	<5.7	y = −5.094x + 154.76	0.067	0.820	0.007
Relative pasture yield (%)	<23	y = −1.288x + 155.92	0.104	0.810	0.001
Corn silage tillable area (%)	>21	y = 1.074x + 103.67	0.095	0.781	0.002
Pasture tillable area (%)	<19	y = −1.323x + 150.60	0.077	0.815	0.001
y = N fertilizer imports (kg ha^{-1})					
Corn silage yield (Mg of DM ha^{-1})	>8.7	y = 1.817x + 39.39	0.052	0.675	0.002
Haylage CP concentration (%)	>17	y = 4.776x – 23.94	0.068	0.657	0.003
Relative corn silage N yield (%)	>16	y = 0.617x + 45.51	0.055	0.652	0.013
Corn silage tillable area (%)	>22	y = 0.837x + 37.60	0.109	0.652	0.003
y = P feed imports (kg ha^{-1})					
Home-grown feed (%)	<69	y = −0.496x + 55.25	0.265	0.776	<0.001
Home-grown forage (%)	<66	y = −0.398x + 47.59	0.169	0.811	<0.001
Home-grown P (%)	<56	y = −0.485x + 48.09	0.435	0.807	<0.001
P in all feed (%)	>0.37	y = 53.85x + 1.11	0.084	0.751	<0.001
P in purchased feed (%)	>0.56	y = 27.09x + 6.08	0.090	0.791	<0.001
Pasture yield (Mg of DM ha^{-1})	<2.1	y = −0.680x + 22.56	0.053	0.757	0.023
Relative pasture yield (%)	<10	y = −0.188x + 22.95	0.096	0.756	0.003
Corn silage P concentration (%)	>0.23	y = 31.16x + 13.83	0.067	0.766	0.005
Corn silage tillable area (%)	>37	y = 0.156x + 15.36	0.086	0.729	0.007
Pasture tillable area (%)	<6	y = −0.214x + 22.38	0.090	0.752	0.001
y = P fertilizer imports (kg ha^{-1})					
Relative corn silage yield (%)	>69	y = 0.056x + 1.31	0.067	0.692	0.013

[1]R^2m = marginal coefficient of variation; R^2c = conditional coefficient of variation.

[2]Relative areas and yields of forage crops (corn silage, haylage, and pasture) are calculated as a percentage of total forage crops on the farm.

imports through feed were less pronounced. However, the division of farm area between the most common crops (corn silage, haylage, and pasture), as well as the resulting DM yield from each of these crops, showed potential as KPI for predicting feed nutrient imports and exceeding the threshold of feed nutrient imports to meet feasible NMB.

For fertilizer nutrient imports, fewer potential KPI showed direct relationships, and most of the significant relationships were related, either directly or indirectly, to the (relative) amount of corn silage grown on the farm. This may be explained by the fact that most hay fields included some legume species, reducing the need for N fertilizer. In contrast, corn silage generally requires higher mineral fertilizer inputs. This is further supported by the fact that the relationship was stronger for N fertilizer imports than for P fertilizer imports. This indicates that farmers tend to be (partly) dependent on mineral fertilizer additions for meeting crop N requirements, whereas crop P requirements can mostly be supplied through manure applications alone. Other potential second-tier KPI, such as the ratio between mature cows and heifer AU, milk CP levels, and cow weight (Table 4), did not show a direct relationship with feed or fertilizer nutrient imports ($P > 0.05$).

The significant relationships between the KPI in Table 5 and nutrient imports in feed and fertilizer indicate that at least part of the need for both feed and fertilizer imports depends on the relative contribution of the different forage crops to home-grown feed. This suggests that KPI connected to these crops (e.g., relative area and DM yield) could be used as tangible second-tier KPI to guide future nutrient management in more detail. The ratio of corn silage to haylage area may not only determine the necessity of fertilizer imports, but the resulting crop DM yields and nutrient contents will also determine the home-grown forage base for the diet (as grass-legume mixtures, for example, contain more CP, whereas corn silage has a higher energy content). Subsequently, this will affect the feed import needs to supplement the forage to achieve optimal rumen function and maximize milk production and fertility. This raises the question whether an ideal composition of home-grown forage crops exists from a

Table 6. Minimal mixed linear models predicting farm-gate nitrogen (N) balances from existing and new key performance indicators[1]

	Existing indicator[3]					
	y = N balance (kg ha^{-1})			y = N balance (kg Mg^{-1} milk exported)		
Fixed effect[2]	β (SE)	Adj. β	*P*-value	β (SE)	Adj. β	*P*-value
(Intercept)	−72.1 (71.5)	−72.1	<0.001	5.42 (7.21)	5.42	0.454
CP in all feed (%)	382.0 (72.1)	7,800.0	<0.001	28.80 (7.27)	587.00	<0.001
Feed use (Mg of DM AU^{-1})	289.0 (35.2)	2,930.0	<0.001	22.20 (3.54)	225.00	<0.001
Home-grown feed (%)	−278.0 (49.6)	−24,200.0	<0.001	−22.60 (4.98)	−1,970.00	<0.001
CP in home-grown feed (%)	−234.0 (56.0)	−4,220.0	<0.001	−18.40 (5.65)	−333.00	0.001
Animal density[4] (AU ha^{-1})	209.0 (35.4)	779.0	<0.001	1.12 (3.58)	4.35	0.745
Random effect	Var (SD)			Var (SD)		
σ^2	812.0 (28.5)			8.11 (2.85)		
τ^{00} Farm	1,060.0 (32.6)			11.10 (3.34)		
τ^{00} Year	0.00 (0.00)			0.04 (0.21)		
R^2m[3] (fixed effects)	0.612			0.297		
R^2c (fixed + random effects)	0.832			0.704		
AICc	1,380.000			762.000		

[1]Factors farm and year are included in the random effects. The model did not identify new indicators as significant, so only existing indicators are included here. Models were generated using 141 observations, 3 yr, and 47 farms.

[2]R^2m = marginal coefficient of variation; R^2c = conditional coefficient of variation; AICc = second-order Akaike information criterion for small sample sizes. Sigma = standard deviation; tau = Kendall rank coefficient.

[3]Values for the adjusted β and SD are obtained by unscaling values for β and SD (see Materials and Methods section). β = regression coefficient; Var = variance.

[4]AU = animal unit = 454 kg (1,000 lbs) of animal weight (cows, heifers, calves).

NMB perspective. The current database does not contain enough information to answer this question. Most of the KPI currently used in NMB assessments relate to NUE in the feed aspect of the whole-farm system. However, more detailed information on nutrient use in soil and crops is required to improve our understanding of nutrient sustainability and efficiency on dairy farms. Examples of potentially useful information include a log of soil types and yield potentials across the farm, a combination of field-scale nutrient balances, accurate yield data, an improved record of legume use and crop nutrient analysis (especially in pastures), and additional information on the management and application of manure and fertilizer sources.

Combining Indicators in Regression Models

Combining multiple KPI in a statistical model and removing potential error or noise can allow additional potential KPI to be identified. The linear mixed effects model that used a combination of existing KPI was able to explain 61% of the variance for the N balances per hectare (Table 6). Commonly used KPI, such as animal density, amount of home-grown feed, and feed CP concentration were included.

The same model explained less of the variation in balances per megagram of milk exported (R^2m = 0.30), and animal density was no longer a significant factor in the model. This implies that farms with a high animal density are not necessarily more or less efficient in their production than more extensive farms, which has been documented previously (Cela et al., 2014).

The inclusion of random factors (farm and year) increased R^2 values to 0.83 (for NMB per hectare) and 0.70 (for NMB per megagram of milk exported), indicating that there was significant variation among farms and, to a lesser extent, between balance years. When potential new KPI were included in the model selection, none were significant.

To explain variation in P balances, a model with KPI similar to those for N was obtained (Table 7), with R^2m values of 0.58 and 0.39 for balances per hectare and per megagram milk exported. As with the N balance models, the same KPI used in the minimal P balance per hectare model can be used to predict the P balance per megagram milk sold, with animal density being a significant KPI for P balance per hectare but not P balance per megagram milk. When new KPI are considered, total home-grown crop DM yield was included as a significant KPI, with farms that achieve higher yields having lower P balances per ha. This improved the R^2m values significantly (Table 7). Adding average crop yield also led to the removal of P in purchased feed from the model, which means that the balance between P concentrations in home-grown and imported feed was explained by one indicator instead of 2.

Table 7. Minimal mixed linear models predicting farm-gate phosphorus (P) balances with existing indicators and with existing + new indicators[1]

	Existing indicator[3]					
	y = P balance (kg ha^{-1})			y = P balance (kg Mg^{-1} milk exported)		
Fixed effect[2]	β (SE)	Adj. β	*P*-value	β (SE)	Adj. β	*P*-value
(Intercept)	19.1 (8.16)	19.10	0.021	2.76 (0.72)	2.76	<0.001
Home-grown feed (%)	−59.6 (6.64)	−5,190.00	<0.001	−4.90 (0.59)	−427.00	<0.001
P in purchased feed (%)	35.7 (4.81)	30.20	<0.001	3.56 (0.43)	3.02	<0.001
Feed use (Mg of DM AU^{-1})	29.8 (4.27)	303.00	<0.001	2.18 (0.38)	22.10	<0.001
Animal density (AU ha^{-1})	19.9 (4.45)	74.30	<0.001	−0.12 (0.40)	−0.47	0.757
P in all feed (%)	−16.4 (6.71)	−9.10	0.016	−1.99 (0.59)	−1.11	0.001
Random effect	Var (SD)			Var (SD)		
σ^2	11.90 (3.45)			0.09 (0.30)		
τ^{00} Farm	18.20 (4.26)			0.16 (0.40)		
τ^{00} Year	0.00 (0.00)			0.00 (0.00)		
R^2m (fixed effects)	0.579			0.394		
R^2c (fixed + random effects)	0.833			0.779		
AICc	818.000			166.000		
	Existing + new indicator					
	y = P balance (kg ha^{-1})			y = P balance (kg Mg^{-1} milk exported)		
Fixed effect	β (SE)	Adj. β	*P*-value	β (SE)	Adj. β	*P*-value
(Intercept)	−8.79 (8.12)	−8.79	0.281	−0.01 (0.74)		0.990
P in all feed (%)	60.80 (8.09)	33.80	<0.001	5.26 (0.74)		<0.001
P in home-grown feed (%)	−60.30 (6.97)	−36.70	<0.001	−5.51 (0.64)		<0.001
Feed use (Mg of DM AU^{-1})	39.60 (5.41)	402.00	<0.001	3.25 (0.49)		<0.001
Animal density (AU ha^{-1})	30.20 (5.77)	113.00	<0.001	1.10 (0.53)		0.040
Home-grown feed (%)	−28.70 (6.08)	−2,500.00	<0.001	−1.80 (0.55)		0.002
Average crop yield (Mg of DM ha^{-1})	−13.90 (5.86)	−227.00	0.020	−1.63 (0.54)		0.003
Random effect	Var (SD)			Var (SD)		
σ^2	10.60 (3.26)			0.09 (0.30)		
τ^{00} Farm	16.10 (0.40)			0.14 (0.38)		
τ^{00} Year	0.16 (3.26)			0.00 (0.04)		
R^2m (fixed effects)	0.618			0.415		
R^2c (fixed + random effects)	0.849			0.778		
AICc	798.000			158.000		

[1]Factors farm and year are included in the random effects. Models were generated using 141 observations, 3 yr, and 47 farms.

[2]R^2m = marginal coefficient of variation; R^2c = conditional coefficient of variation; AICc = second-order Akaike information criterion for small sample sizes. Sigma = standard deviation; tau = Kendall rank coefficient. AU = animal unit = 454 kg (1,000 lbs) of animal weight (cows, heifers, calves).

[3]Values for the adjusted (adj.) β are obtained by back-scaling the values for β (see Materials and Methods section). β = regression coefficient; Var = variance.

Selection of yield-based indicators (average crop yield for P balances) may indicate that a better understanding of the soil-crop management aspect could help in the search for new KPI and an improved prediction of NMB. Keeping track of and reporting yields and nutrient contents of the main crops on-farm may therefore be used in NMB assessments to further elucidate the drivers of high N and P balances. Although obtaining accurate data would require extra effort through measurements and record keeping, the additional opportunities to improve NMB, efficiency, and the environmental footprint of the farm, could make taking the extra data collection step more appealing to farmers.

For the drivers of nutrients imported in feed and fertilizer purchases, all potential KPI were considered (Table 8). The minimal models for feed nutrient imports included a wide range of KPI to explain a large amount of the variation (R^2m = 0.97 for N and R^2m = 0.96 for P). Some KPI, such as milk yield per cow or feed nutrient concentrations, were included for the feed N model, but not for the feed P model. This may reflect that milk yield is more often limited by diet CP than diet P as many feeds have P compositions that exceed the

Table 8. Minimal mixed linear models predicting nitrogen (N) and phosphorus (P) imports of feed and fertilizers[1]

	Feed import[3]					
	y = N feed imports (kg ha^{-1})			y = P feed imports (kg ha^{-1})		
Fixed effect[2]	β (SE)	Adj. β[2]	*P*-value	β (SE)	Adj. β	*P*-value
(Intercept)	−126.0 (22.00)	−126	<0.001	−23.00 (3.69)	−23.0	<0.001
CP or P in all feed (%)	384.0 (18.90)	7,820	<0.001	64.00 (3.16)	35.6	<0.001
Animal density (AU ha^{-1})[3]	297.0 (12.90)	1,110	<0.001	45.60 (2.29)	170.0	<0.001
CP or P in home-grown feed (%)	−259.0 (16.60)	−4,690	<0.001	−50.40 (2.87)	−30.6	<0.001
Feed use (Mg of DM AU^{-1})	252.0 (12.50)	2,550	<0.001	40.20 (2.21)	408.0	<0.001
Farm-produced feed (%)	−208.0 (14.10)	−18,100	<0.001	−30.20 (2.57)	−2,630.0	<0.001
Avg. crop yield (Mg of DM ha^{-1})	−55.4 (13.30)	−909	<0.001	−10.20 (1.20)	−167.0	<0.001
Relative haylage yield (%)	34.3 (9.60)	3,200	<0.001	4.01 (1.20)	374.0	0.001
Milk yield (Mg cow^{-1})	28.1 (10.70)	395	0.010	4.63 (1.80)	65.1	0.011
Land for home-grown haylage (%)	−26.2 (11.20)	−3,880	0.020			
Random effect	Var (SD)			Var (SD)		
σ^2	55.90 (7.48)			2.08 (1.44)		
τ^{00} Farm	62.40 (7.90)			1.23 (1.11)		
τ^{00} Year	0.00 (0.00)			0.00 (0.04)		
R^2m (fixed effects)	0.968			0.959		
R^2c (fixed + random effects)	0.985			0.974		
AICc	994.000			546.000		
	Fertilizer import					
	y = N fertilizer import (kg ha^{-1})			y = P fertilizer import (kg ha^{-1})		
Fixed effect	β (SE)	Adj. β	*P*-value	β (SE)	Adj. β	*P*-value
(Intercept)	−79.8 (45.1)	−79.8	0.080	11.0 (2.34)	11.00	<0.001
CP in all feed (%)	103.0 (42.4)	2,100.0	0.017			
Relative CP in corn silage (%)	69.8 (20.3)	5,470.0	<0.001			
Feed use (Mg of DM AU^{-1})	63.0 (26.1)	639.0	0.017			
P in home-grown feed (%)				−8.88 (3.65)	−5.40	0.016
Heifer to cow ratio				−4.89 (2.31)	−7.04	0.038
Random effect	Var (SD)			Var (SD)		
σ^2	545.00 (23.30)			6.32 (2.51)		
τ^{00} Farm	982.00 (31.30)			10.30 (3.21)		
τ^{00} Year	2.82 (1.68)			0.14 (0.38)		
R^2m (fixed effects)	0.129			0.061		
R^2c (fixed + random effects)	0.689			0.646		
AICc	1,360.000			746.000		

[1]Factors farm and year are included in the random effects. Models were generated using 141 observations, 3 yr, and 47 farms.

[2]R^2m = marginal coefficient of variation; R^2c = conditional coefficient of variation; AICc = second-order Akaike information criterion for small sample sizes. Sigma = standard deviation; tau = Kendall rank coefficient. AU = animal unit = 454 kg (1,000 lbs) of animal weight (cows, heifers, calves).

[3]Values for the adjusted (adj.) β are obtained by back-scaling the values for β (see Materials and Methods section). β = regression coefficient; Var = variance.

P requirements in dairy cattle diets (NASEM, 2021). In the fertilizer import minimal models, relatively few KPI were retained (Table 8). The explanatory value of the minimal model was relatively low (R^2m = 0.13 for N and R^2m = 0.06 for P), implying that a large amount of the variation in fertilizer N and P imports could neither be explained by the currently used KPI nor the new ones. This is not surprising given no information on manure composition, application rate, timing and method, or soil nutrient resources, is obtained with the current input sheets for the NMB assessment. Additionally, where mineral fertilizer is added in excess of crop needs, a lack of a relationship between fertilizer imports and possible explanatory variables, and thus a lack of fit of the statistical model can be expected. In this farm database, which does not include field specific information, it is uncertain to what extent such additions took place.

The wide variation in farm and management characteristics among dairy farms shows their uniqueness and diversity. Therefore, we observed no one-size-fits-all solution to increase yields (both crop and milk yields) and reduce environmental losses. Likewise, we detected no single KPI to accurately predict a farm's NMB or to help the farmer improve the NUE at the whole-farm scale. Nevertheless, databases such as the one we have used here can provide KPI that help to identify opportunities for improvements in nutrient management on these farms, without the need for additional data beyond what is currently used to derive NMB. These improvements are often farm specific and can entail, for example, the reduction of import of fertilizers, increase of home-grown feed, or the switch toward feed imports with different nutrient stoichiometry. Although some of the more detailed relationships between NMB, imports, and KPI remain unclear, results of this analysis show a combination of current and new KPI derived from inputs for the NMB assessment can be used to indicate a farm's risk of exceeding feasible NMB.

In addition to statistical modeling tools, such as the ones presented here, (semi)mechanistic whole-farm models could be used to increase our understanding of nutrient cycling, efficiency, and sustainability on dairy farms, as well as what is driving these processes. Even though whole-farm models to predict nutrient use are available (Cabrera et al., 2006; Groot et al., 2006; Rotz et al., 2018) and work is ongoing to develop a more mechanistic model for whole-farm environmental footprint evaluation, including NUE (Kebreab et al., 2019; Hansen et al., 2021), it should be recognized that assessment for nutrient use using the annual NMB assessment results in meaningful KPI that farmers, nutritionists, and crop advisors can use to determine opportunities for improvements without compromising milk yield. Reporting of second-tier KPI, such as the relative area, DM yields, and nutrient contents for the primary crops produced on dairy farms may provide deeper insight into the drivers of NMB and enhance their value to dairy farmers. Furthermore, expansion of the assessment to include additional commonly used metrics that already guide management decisions such as milk urea nitrogen (Kauffman and St-Pierre, 2001; Spek et al., 2013), corn stalk nitrate test (Binford et al., 1990; Maresma et al., 2019), soil test P and other soil nutrients, manure composition and application practices (rate, method, timing), yield variability across and within fields, and yield-derived field nutrient balances (nutrients supplied versus crop uptake and removal with harvest) will help to identify a clearer adaptive and continuous improvement process for farms.

CONCLUSIONS

Using a 3-yr, 47-farm database, main drivers and potential KPI for NMB of dairy farms were determined. Nutrient balances were driven by nutrient imports, specifically by feed and fertilizer imports. Regression analyses showed that a selection of KPI currently used, such as animal density, nutrient use efficiency, and home-grown feed, were able to explain a significant amount of the variation in nutrient balances and feed imports. New indicators identified in this data set, such as those related to the relative production of forage crops (corn silage and haylage) on the farm, should be added as KPI. We conclude that a limited set of inputs needed to calculate farm-gate NMB can be used to derive actionable KPI. The development of opportunities for improvement can be strengthened with additional information on soil fertility status, crop indicators including yield and nutritive composition, manure management and application strategies, and cow performance.

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REFERENCES

Anderson, B. H., and F. R. Magdoff. 2000. Dairy farm characteristics and managed flows of phosphorus. Am. J. Altern. Agric. 15:19–25. https://doi.org/10.1017/S0889189300008420.

Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67:1–48. https://doi.org/10.18637/jss.v067.i01.

Binford, G. D., A. M. Blackmer, and N. M. El-Hout. 1990. Tissue test for excess nitrogen during corn production. Agron. J. 82:124–129. https://doi.org/10.2134/agronj1990.00021962008200010027x.

Butterbach-Bahl, K., E. M. Baggs, M. Dannenmann, R. Kiese, and S. Zechmeister-Boltenstern. 2013. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? Philos. Trans. R. Soc. Lond. B Biol. Sci. 368:20130122. https://doi.org/10.1098/rstb.2013.0122.

Cabrera, V. E., P. E. Hildebrand, J. W. Jones, D. Letson, and A. De Vries. 2006. An integrated North Florida dairy farm model to reduce environmental impacts under seasonal climate variability. Agric. Ecosyst. Environ. 113:82–97. https://doi.org/10.1016/j.agee.2005.08.039.

Cela, S., Q. M. Ketterings, K. Czymmek, M. Soberon, and C. Rasmussen. 2014. Characterization of nitrogen, phosphorus, and potassium mass balances of dairy farms in New York State. J. Dairy Sci. 97:7614–7632. https://doi.org/10.3168/jds.2014-8467.

Cela, S., Q. M. Ketterings, K. Czymmek, M. A. Soberon, and C. N. Rasmussen. 2015. Long-term trends of nitrogen and phosphorus mass balances on New York State dairy farms. J. Dairy Sci. 98:7052–7070. https://doi.org/10.3168/jds.2015-9776.

Cela, S., Q. M. Ketterings, K. J. Czymmek, J. Weld, D. B. Beegle, and P. J. A. Kleinman. 2016. Nutrient management planners' feedback on New York and Pennsylvania phosphorus indices. J. Soil Water Conserv. 71:281–288. https://doi.org/10.2489/jswc.71.4.281.

Cela, S., Q. M. Ketterings, M. A. Soberon, C. N. Rasmussen, and K. J. Czymmek. 2017. Upper Susquehanna watershed and New York State improvements in nitrogen and phosphorus mass balances of dairy farms. J. Soil Water Conserv. 72:1–11. https://doi.org/10.2489/jswc.72.1.1.

Cerosaletti, P. E., D. G. Fox, and L. E. Chase. 2004. Phosphorus reduction through precision feeding of dairy cattle. J. Dairy Sci. 87:2314–2323. https://doi.org/10.3168/jds.S0022-0302(04)70053-3.

Correll, D. L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27:261–266. https://doi.org/10.2134/jeq1998.00472425002700020004x.

Czymmek, K. J., Q. M. Ketterings, L. D. Geohring, and G. L. Albrecht. 2003. The New York phosphorus runoff index. User's manual and documentation. Cornell University.

Czymmek, K. J., Q. M. Ketterings, M. Ros, S. Cela, S. Crittenden, D. Gates, T. Walter, S. Latessa, L. Klaiber, and G. Albrecht. 2020. The New York Phosphorus Runoff Index: Version 2.0. User's manual and documentation. Cornell University.

Dairy One. 2021. Dairy One Feed Composition Library. Accessed Oct. 6, 2021. https://dairyone.com/services/forage-laboratory-services/feed-composition-library/.

Fang, Y. 2011. Asymptotic equivalence between cross-validations and Akaike information criteria in mixed-effects models. J. Data Sci. 9:15–21. https://doi.org/10.6339/JDS.201101_09(1).0002.

Fangueiro, D., J. Pereira, J. Coutinho, N. Moreira, and H. Trindade. 2008. NPK farm-gate nutrient balances in dairy farms from Northwest Portugal. Eur. J. Agron. 28:625–634. https://doi.org/10.1016/j.eja.2008.01.007.

Frey, H. C., and S. R. Patil. 2002. Identification and review of sensitivity analysis methods. Risk Anal. 22:553–578. https://doi.org/10.1111/0272-4332.00039.

Gourley, C. J. P., W. J. Dougherty, D. M. Weaver, S. R. Aarons, I. M. Awty, D. M. Gibson, M. C. Hannah, A. P. Smith, and K. I. Peverill. 2012. Farm-scale nitrogen, phosphorus, potassium, and sulfur balances and use efficiencies on Australian dairy farms. Anim. Prod. Sci. 52:929–944. https://doi.org/10.1071/AN11337.

Groot, J. C. J., W. A. H. Rossing, and E. A. Lantinga. 2006. Evolution of farm management, nitrogen efficiency, and economic performance on Dutch dairy farms reducing external inputs. Livest. Sci. 100:99–110. https://doi.org/10.1016/j.livprodsci.2005.08.008.

Hansen, T. L., M. Li, J. Li, C. J. Vankerhove, M. A. Sotirova, J. M. Tricarico, V. E. Cabrera, E. Kebreab, and K. F. Reed. 2021. The ruminant farm systems animal module: A biophysical description of animal management. Animals (Basel) 11:1373. https://doi.org/10.3390/ani11051373.

Hristov, A. N., W. Hazen, and J. W. Ellsworth. 2006. Efficiency of use of imported nitrogen, phosphorus, and potassium and potential for reducing phosphorus imports on Idaho dairy farms. J. Dairy Sci. 89:3702–3712. https://doi.org/10.3168/jds.S0022-0302(06)72411-0.

Kauffman, A. J., and N. R. St-Pierre. 2001. The relationship of milk urea nitrogen to urine nitrogen excretion in Holstein and Jersey cows. J. Dairy Sci. 84:2284–2294. https://doi.org/10.3168/jds.S0022-0302(01)74675-9.

Kebreab, E., K. F. Reed, V. E. Cabrera, P. A. Vadas, G. Thoma, and J. M. Tricarico. 2019. A new modeling environment for integrated dairy system management. Anim. Front. 9:25–32. https://doi.org/10.1093/af/vfz004.

Ketterings, Q. M., and K. J. Czymmek. 2012. Phosphorus index as a phosphorus awareness tool: Documented phosphorus use reduction in New York State. J. Environ. Qual. 41:1767–1773. https://doi.org/10.2134/jeq2012.0050.

Ketterings, Q. M., K. J. Czymmek, and S. N. Swink. 2011. Evaluation methods for a combined research and extension program used to address starter phosphorus fertilizer use for corn in New York. Can. J. Soil Sci. 91:467–477. https://doi.org/10.4141/cjss10001.

Ketterings, Q. M., S. N. Swink, G. Godwin, K. J. Czymmek, and G. L. Albrecht. 2005. Maize silage yield and quality response to starter phosphorus fertilizer in high phosphorus soils in New York. J. Food Agric. Environ. 3:237–242.

Koelsch, R. 2005. Evaluating livestock system environmental performance with whole-farm nutrient balance. J. Environ. Qual. 34:149–155.

Maresma, A., P. Berenguer, R. S. Breslauer, A. C. Tagarakis, T. P. Kharel, K. J. Czymmek, and Q. M. Ketterings. 2019. In-field spatial variability of corn stalk nitrate test results. Agron. J. 111:2864–2873. https://doi.org/10.2134/agronj2019.02.0080.

Mihailescu, E., P. N. C. Murphy, W. Ryan, I. A. Casey, and J. Humphreys. 2015. Phosphorus balance and use efficiency on 21 intensive grass-based dairy farms in the South of Ireland. J. Agric. Sci. 153:520–537. https://doi.org/10.1017/S0021859614000641.

Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining R^2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4:133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x.

NASEM. 2021. Nutrient Requirements of Dairy Cattle. 8th rev. ed. The National Academies Press.

Nutrient Management Spear Program, New York State Department of Agriculture and Markets, Natural Resources Conservation Service, and New York State Department of Environmental Conservation. 2018. Adaptive Management and In-Season N Application Update Expanded End-of-Season Evaluation Options for Corn. Accessed Aug. 11, 2021. http://nmsp.cals.cornell.edu/publications/files/AdaptiveManagementGuidelines.pdf.

Öborn, I., A. C. Edwards, E. Witter, O. Oenema, K. Ivarsson, P. J. A. Withers, S. I. Nilsson, and A. Richert Stinzing. 2003. Element balances as a tool for sustainable nutrient management: A critical appraisal of their merits and limitations within an agronomic and environmental context. Eur. J. Agron. 20:211–225. https://doi.org/10.1016/S1161-0301(03)00080-7.

Oenema, O., H. Kros, and W. De Vries. 2003. Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies. Eur. J. Agron. 20:3–16. https://doi.org/10.1016/S1161-0301(03)00067-4.

Pearce, A., and R. Maguire. 2020. The state of phosphorus balance on 58 Virginia dairy farms. J. Environ. Qual. 49:324–334. https://doi.org/10.1002/jeq2.20054.

Quemada, M., L. Lassaletta, L. S. Jensen, O. Godinot, F. Brentrup, C. Buckley, S. Foray, S. K. Hvid, J. Oenema, K. G. Richards, and O. Oenema. 2020. Exploring nitrogen indicators of farm performance among farm types across several European case studies. Agric. Syst. 177:102689. https://doi.org/10.1016/j.agsy.2019.102689.

Ros, M. B. H., K. J. Czymmek, and Q. M. Ketterings. 2018. Creating nutrient sustainability indicators for dairies nationwide. Page 8 in Proc. Cornell Nutrition Conference. Cornell University.

Rotz, C. A., M. S. Corson, D. S. Chianese, F. Montes, S. D. Hafner, H. F. Bonifacio, and C. U. Coiner. 2018. The Integrated Farm System Model—Reference Manual Version 4.4. Agricultural Research Service, USDA.

Ruane, E. M., M. Treacy, K. McNamara, and J. Humphreys. 2014. Farm-gate phosphorus balances and soil phosphorus concentrations on intensive dairy farms in the south-west of Ireland. Ir. J. Agric. Food Res. 53:105–119.

Scavia, D., J. David Allan, K. K. Arend, S. Bartell, D. Beletsky, N. S. Bosch, S. B. Brandt, R. D. Briland, I. Daloğlu, J. V. DePinto, D. M. Dolan, M. A. Evans, T. M. Farmer, D. Goto, H. Han, T. O. Höök, R. Knight, S. A. Ludsin, D. Mason, A. M. Michalak, R. Peter Richards, J. J. Roberts, D. K. Rucinski, E. Rutherford, D. J. Schwab, T. M. Sesterhenn, H. Zhang, and Y. Zhou. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. J. Great Lakes Res. 40:226–246. https://doi.org/10.1016/j.jglr.2014.02.004.

Scharf, P. 2015. Managing Nitrogen in Crop Production. ACSESS Publications.

Sinclair, K. D., P. C. Garnsworthy, G. E. Mann, and L. A. Sinclair. 2014. Reducing dietary protein in dairy cow diets: Implications for nitrogen utilization, milk production, welfare, and fertility. Animal 8:262–274. https://doi.org/10.1017/S1751731113002139.

Soberon, M. A., S. Cela, Q. M. Ketterings, C. N. Rasmussen, and K. J. Czymmek. 2015. Changes in nutrient mass balances over time and related drivers for 54 New York State dairy farms. J. Dairy Sci. 98:5313–5329. https://doi.org/10.3168/jds.2014-9236.

Soberon, M. A., Q. M. Ketterings, C. N. Rasmussen, and K. J. Czymmek. 2013. Whole farm nutrient balance calculator for New York dairy farms. Nat. Sci. Educ. 42:57–67. https://doi.org/10.4195/nse.2012.0020.

Spears, R. A., R. A. Kohn, and A. J. Young. 2003a. Whole-farm nitrogen balance on western dairy farms. J. Dairy Sci. 86:4178–4186. https://doi.org/10.3168/jds.S0022-0302(03)74033-8.

Spears, R. A., A. J. Young, and R. A. Kohn. 2003b. Whole-farm phosphorus balance on western dairy farms. J. Dairy Sci. 86:688–695. https://doi.org/10.3168/jds.S0022-0302(03)73648-0.

Spek, J. W., J. Dijkstra, G. van Duinkerken, W. H. Hendriks, and A. Bannink. 2013. Prediction of urinary nitrogen and urinary urea nitrogen excretion by lactating dairy cattle in northwestern Europe and North America: A meta-analysis. J. Dairy Sci. 96:4310–4322. https://doi.org/10.3168/jds.2012-6265.

USDA-ERS (USDA Economic Research Service). 2022. Dairy Data. Accessed Dec. 5, 2022. https://www.ers.usda.gov/data-products/dairy-data/documentation/

USDA-NASS (USDA National Agricultural Statistics Service). 2019. 2017 Census of Agriculture.

USDA-NASS (USDA National Agricultural Statistics Service). 2020. 2019–2020 Agricultural statistics annual bulletin: New York.

USDA-NASS (USDA National Agricultural Statistics Service). 2021a. 2020 State Agriculture Overview for New York. Accessed Jul. 28, 2021. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEW YORK.

USDA-NASS. 2021b. 2020 State Agriculture Overview for Vermont. Accessed Jul. 28, 2021. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=VERMONT.

Ussiri, D., and R. Lal. 2013. Soil Emission of Nitrous Oxide and Its Mitigation. Springer.

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