Moving Virginia Dairy Farms Toward Phosphorus Balance

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ACADEMIC ABSTRACT

Sustainability for Virginia dairy farms requires balancing phosphorus (P) imports and exports at the farm-gate level. Balancing P helps prevent further accumulation of P in farm soils through routine applications of manure, which over time contributes to surface water quality issues. The objectives of this research centered on guiding dairy farms in Virginia toward lower, more sustainable P balance, and without adversely impacting profitability. First, the state of P balance had to be determined for a sample of dairy farms, including risk factors for excessively high P balance. Second, a repeated assessment of P balance on those dairy farms sought to determine any key factors of change in P balance between years. Lastly, a small Virginia dairy farm was used as a case farm to evaluate whether or not it could reduce its P balance while maintaining or improving farm profitability. An initial assessment of 58 dairy farms in Virginia showed that 75% of farms could operate with a P balance less than 18.7 kg ha^{-1}. The two risk factors that led to excessively high P surpluses were the use of poultry litter and excessive P imported with purchased feed. The repeated assessment included 30 of the 58 original dairy farms. Increases of 1.0 kg P ha^{-1} of total P imports and exports were respectively correlated to a mean P balance increase of 0.76 kg ha^{-1} and a mean P balance decrease of 0.43 kg ha^{-1}, suggesting that changes in P imports affect changes in P balance more than changes in P exports. Reduced poultry litter use was highly correlated to reduced P balance, and increasing cow manure exports also reduced P balance for the farms with the opportunity. As a significant portion of the farms assessed were small (less than 200 milking cows), a case farm of 105 cows on 100 acres was used to explore how farm profitability could be affected as P balance was reduced through additional acres, increased crop production, and with a grazing-based farming strategy. Results from partial budget analysis showed that after expanding the land base from 100 to 150 acres for crop production, the change in potential net return ranged from $-0.90 to $1.26/cwt of milk, with accompanying changes in P balance ranging from -9.0 to -14.7 lbs/ac. The analysis also showed that changes in potential net returns after converting to a grazing-based system ranged from $-2.14 to $1.39/cwt, with greater change in P balance ranging from -9.7 to -17.8 lbs/ac. The most profitable strategy, generally, for this farm seemed to be expanding the land base and growing a cash crop. Phosphorus balance on Virginia dairy farms can be reduced, potentially without negative impacts on farm net return, though challenges remain for farms with limited land or areas with high density of animal agriculture.

Moving Virginia Dairy Farms Toward Phosphorus Balance

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GENERAL AUDIENCE ABSTRACT

Phosphorus (P) is a vital nutrient for crops and livestock, but too much of it in soils leads to surface water quality problems. Sustainability for Virginia dairy farms requires balancing P imports and exports at the farm level. This research centered on guiding dairy farms in Virginia toward lower, more sustainable P balance. An initial assessment of 58 dairy farms in Virginia helped establish a zone of operation, a feasible target toward which the 25% of farms with high P balance could aim. Avoiding poultry litter as a fertilizer choice and limiting P imported with purchased feed were both ways in which some of these farms could lower their P balance. A repeated assessment in a second year showed that reductions in P imported were more likely to reduce P balance than were increasing P exports. In this, reducing the use of poultry litter as a fertilizer was again an effective way of lowering P balance. As a significant portion of the farms assessed were small (less than 200 milking cows), a case farm of 105 cows on 100 acres was used to explore how farm profitability could be affected as P balance was reduced through various management changes. Results showed that after expanding the land base by at least 50 acres for additional crop production, P balance could be significantly reduced while maintaining or increasing the potential net return to the farmer, especially if the farmer can ensure a high milk yield grazing-based operation or if they grow a cash crop like corn or soybeans. Overall, the research suggests that P balance on Virginia dairy farms can be reduced, and that these farms can operate more sustainably, though challenges remain for farms with limited land or areas with high density of animal agriculture.

Dedication

To my absolutely most wonderful wife, Madison.

And to my children, Ronan, Clarissa, and Anton.

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My committee chair and advisor Rory Maguire has been a critical force in my progress these past few years, learning many things pertaining to work as a scientist as well as leadership and family life. My success has also due to the helpful interactions and counseling I received from committee members Katharine Knowlton, Meredith Steele, and Alex White. I thank them as well as other professors like Matt Eick for their instruction and motivation throughout my program and during the difficult moments.

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Introduction

Nonpoint source P pollution is a key factor in freshwater eutrophication, and agriculture represents a significant portion of all nonpoint source pollution (Carpenter et al., 1998). Agriculture influences both the overall balance or flow of P into and from systems as well as the cycling of P in the soil system and environment (Foy, 2005). An example of this is the way in which the dairy farm production cycle draws P up from the soil, with soil P concentrating near the soil surface. This occurs through the cycle of crop removal, animal feeding, and surface applications of animal manure on the next crop, which cycling can lead to significant soil heterogeneity across the farm landscape (Gourley et al., 2015). When soil P concentrations are elevated above agronomic requirements, managing P in these agricultural soils becomes critical for minimizing the risk of P transport to surface waters (Sharpley and Withers, 1994).

Much research has gone into minimizing the risk of soil P to contaminate water quality downstream. This large body of research includes concepts of P risk indices, critical source areas, P fractionation, subsurface transport of dissolved P, and so on. Risk indices aim better management at high risk fields or catchments (Lemunyon and Gilbert, 1993; Buchanan et al., 2013; Thomas et al., 2016). Neither risk indices nor runoff and erosion controls, however, can prevent the underlying cause of high soil P: imbalances of P inputs and outputs on animal farms and in areas of concentrated animal agricultural production.

At regional scales, animal agriculture has fundamentally changed the global cycle of P in 100 years (Bouwman et al., 2009, 2013). Global and regional flows of phosphorus as fertilizer or feed or manure have led to depletions and accumulations in distinct geographic areas (Maguire et al., 2007; Reid et al., 2019). In summary, the main concern is that neither controlling P cycling within a closed system nor attempting to limit P losses to the environment effectively address the underlying mass imbalance of P on dairy farms. This dissertation presents research relevant to Virginia dairy farming and nutrient management, building off previous P balance work done around the world.

Objectives

The general focus of this dissertation was to understand the nature of P mass balances on Virginia dairy farms. Three chapters resulted from this study:

Chapter 1

A. Determine P mass balances on Virginia dairy farms, especially those within the Chesapeake Bay Watershed.
B. Define potential guidelines fora sustainable and feasible zone of operation for Virginia dairy farms based on P balance and P use efficiency.
C. Reveal risk factors leading to P surplus and P use inefficiencies on the dairy farms, especially for those farms in the highest quartile of P surplus.

Chapter 2

A. Perform a subsequent P mass balance assessment for participating dairy farms in Virginia after the first round of assessment and farmer education.
B. Reveal key factors of any change observed in P balance.

Chapter 3

A. Evaluate if a small Virginia dairy farm can lower its P surplus and improve its P use efficiency while maintaining or improving farm profitability.

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Chapter 1: The State of Phosphorus Balance on 58 Virginia Dairy Farms

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Abstract

Managing a sustainable dairy farm requires balancing phosphorus (P) imports and exports that enter and leave through the farm-gate. Over the long-term, P surpluses will elevate soil test P concentrations above crop requirements through routine land applications of manure. The objectives of this study were aimed at Virginia dairy farms, and were to: 1) determine P mass balances; 2) define potential guidelines for a sustainable and feasible zone of operation based on P balance and P use efficiency; 3) assess risk factors leading to P surplus and P use inefficiencies. Data on farm-gate P imports and exports via feed, manure, crops, fertilizers, bedding, animals and milk were collected for 58 dairy farms in Virginia. There was no relationship between farm P balance and milk production, indicating a P surplus was not necessary for good milk productivity. A feasible P balance limit was calculated below which 75% of farms could operate, and this was 18.7 kg-P ha-1. Two risk factors were identified for farms having a P balance above this limit, and they were a) land application of poultry litter, and b) excessive import of P through feed. Combined dairy and beef operations generally had more land and a lower P balance, while having combined dairy and poultry did not raise the P balance as long as poultry litter was exported. Dairy farms in Virginia can operate with a sustainable P balance as long as they avoid using excessive poultry litter and pay attention to P imported through purchased feed.

Introduction

Managing a sustainable dairy farm requires balancing phosphorus (P) imports and exports that enter and leave through the farm-gate (Oenema et al., 2003). Phosphorus imports for a dairy farm may include purchased feeds and supplements, commercial fertilizers and animal byproducts such as manure or poultry litter, bedding materials, etc., from an off-farm source (Koelsch, 2005). For a dairy farm, P exports may include crops and animals sold, manure or compost taken off-farm, and milk. The difference in the quantity of P imported onto and exported from a dairy farm during a year is the annual P mass balance (Oenema et al., 2003).

Two problems can occur with recurring P mass imbalance, or when annual P imports are not routinely balanced with annual P exports over many years, and both jeopardize dairy farm sustainability. First, net P exportation (negative balance) or P shortage results in soil P drawdown through crop uptake and product exports. In the short term, net P exportation is ideal for dairy farms with soils at elevated soil test P concentrations (Oenema et al., 2003). Drawdown of soil P can continue until soil test concentrations approach agronomic thresholds, at which point crop yields may experience P deficiency symptoms.

The second and more common problem is net P importation (positive balance) or P surplus, resulting in some degree of nutrient use inefficiency, soil P accumulation, and, eventually, increased environmental losses (Spears et al., 2003). Over the long-term, P surpluses will elevate soil test P concentrations far above crop requirements through routine land applications of manure (Wang et al., 1999). When soil P concentrations in agricultural soils are sustained above agronomic requirements, managing P becomes increasingly important to minimize risks of P transport to natural surface waters, where P contributes to eutrophication and degradation of water resources (Sharpley and Withers, 1994; Carpenter et al., 1998).

The effects of P mass imbalances have been observed at regional and global levels, with P cycled through fertilizers, feeds, and manures leading to soil P depletions and accumulations in distinct geographic areas (Maguire et al., 2007; Bouwman et al., 2009). These region-level P surpluses were, in part, the result of efficient infrastructure and logistics in transporting animal feed over long distances (Maguire et al., 2007).

The problem of surplus P on dairy farms is often driven by the additions of imported feed concentrates. These are added to the total mixed rations of the animals to ensure nutritional requirements are met, which can result in supplying some nutrients like P above recommended levels (Anderson and Magdoff, 2000). Any excess P in animal rations is not absorbed during digestion, but is excreted in manure and urine (Knowlton and Herbein, 2002; Dou et al., 2002). For example, dried distillers grains may be included for protein while oversupplying P (Maguire, 2014). Since total mixed rations often have P at higher concentrations than necessary (Dou et al., 2003), imported feed can ultimately be considered a fertilizer import as the manure ends up being land applied.

Besides imported feed, other manageable factors can increase the risk of P surplus on a dairy farm. Certain risk factors related to excessive, positive P balance were determined on a sample of New York dairy farms in 2006 (Cela et al., 2014), with some farms repeatedly measured in following years (Cela et al., 2015b; Soberon et al., 2015). From these studies, some risk factors for P surplus on dairy farms included: animal density being greater than 2.4 AU ha^{-1} (1 AU = 454 kg = 1000 lbs of animal weight), producing less than ~63% of dry matter feed, P content greater than 0.6% in imported feed, and exporting less than 1 kg-P ha^{-1} through manure or crops to balance imports. Dairy farms operating under multiple risk factors tended to be in the highest quartile of farms for P balance, with the greatest potential for P balance reductions (Cela et al., 2014).

Management of risk factors to reduce P surplus can be adapted on a farm-by-farm basis according to the needs of the dairy producer (Ketterings, 2014). For example, increasing yields and crop quality in exported crops can increase export of P off the farm (Cela et al., 2015b). Crop exports can also increase revenue, and is particularly important on dairy farms with lower animal density (Cela et al., 2014). Increasing milk exports cannot to be reasonably considered as a strategy for balancing P through exports as increased inputs are usually required for potentially marginal increases in milk produced. Organic farms, for instance, operate at lower milk production per cow than conventional dairies (Sato et al., 2005) , and may also be at greater risk for P imbalance due to fertilizer and feed constraints of certified organic programs.

Exporting manure off-farm also decreases P surplus and improves P balance and nutrient use efficiency, especially on farms with higher animal densities (> 2.4 animal unit ha^{-1}) (Cela et al., 2014). Many factors limit manure export, including: timing, availability, storage, and transportation. Trends in dairy farm consolidation and agricultural intensification further limit manure transport options as the localized demand for manure nutrients diminishes around manure sources (Blayney, 2002; Gerber et al., 2010). Cultivating a market for manure was reported to be necessary in the Chesapeake Bay Watershed as a means to distribute manure to nutrient-deficient farm lands rather than continued accumulation of nutrients around the source. (Kleinman et al., 2012).

The importance of balancing P on dairy farms in Virginia has been recognized (Maguire, 2014). Therefore, the objectives of this study were to: 1) determine P mass balances on Virginia dairy farms, especially those within the Chesapeake Bay Watershed; 2) define potential guidelines fora sustainable and feasible zone of operation for Virginia dairy farms based on P balance and P use efficiency; 3) reveal risk factors leading to P surplus and P use inefficiencies on the dairy farms, especially for those farms in the highest quartile of P surplus.

Materials and Methods

Sampling

Virginia dairy farms within the Chesapeake Bay Watershed were targeted for sampling due to the association between animal agriculture and water quality concerns in the Bay. Sampling was not designed to be stratified or random, but was based on farmer willingness to participate and gaining maximum participation. Dairy farms were invited to participate in the study through various modes of contact. Some farms with working relationships with state employees and extension agents were invited during regular farm visits. The study was also introduced to different groups at various nutrient management workshops, stakeholder meetings, etc.

The P balance calculations were conducted for the 2017 calendar year, accounting for all P imports and exports that passed through the farm gate between January 1 and December 31 of 2017. Phosphorus mass balances for 2017 were calculated for 58 dairy farms in 2018. This sample included both small, unregulated dairy farms (<200 mature dairy cows) as well as larger, regulated dairy farms. Regulated dairy farms are required to have state approved nutrient management plans (VA DEQ, 2019). The sample also represented some mixed-operation dairy farms that had poultry and/or beef enterprises in addition to dairies.

Visits and Data Collection

Data collection required input from dairy producers, nutritionists, and feed suppliers. Much of the data collection was conducted face-to-face, on-farm, in order to ease the process for busy, volunteering producers. A data collection sheet was prepared to standardize information gathering, asking for certain farm characteristics, P imports, and P exports. Farm characteristics included average animal numbers and weights, land base size, proportion of land that receives manure applications, whether the producer uses grazing strategies as a significant part of their feeding practices, and whether the producer is certified organic. Imports of P were feed purchased, fertilizers or animal manure and litter, animals purchased, and bedding materials. Exports were milk sold, animals sold, crops sold, and animal manures exported off-farm.

On mixed-operation dairy farms with beef cattle, the imports and exports also accounted for the beef cattle. Beef cattle have lower impacts on farm-gate P imports than dairy cows due to beef pasture grazing. On mixed-operation dairy farms with poultry production, 100% of bird feed is imported. Therefore, to account for the presence of poultry in a P balance calculation only requires the balancing of P in poultry litter generated and exported. Poultry birds were not included in animal units for consistency because for farms that export all generated poultry litter, the birds are effectively nonexistent.

Where a producer did not have acceptable information on the P content in feed, feed samples were collected for total P analysis when possible. In all, 16 samples were collected, including diverse feed stuffs such as brewer's and distiller's grains, cottonseed hulls, and dried kelp. Six bedding samples were also collected from various farms because available analyses on materials such as sawdust and wood shavings do not usually include P content. All samples were oven dried at 65 C, finely ground, and 0.5 g of sample was digested in 10 mL of nitric acid using a CEM MARS Xpress microwave system (CEM, 2018). Digested samples were diluted to 50 mL with distilled water, and analyzed on Thermo ICP-AES for total elemental P. Alternatively, relevant standard book values for P concentrations were used if a feed sample was not collected from the dairy farm. Such book values came from the Nutrient Requirements of Dairy Cattle or the Dairy One online database (NRC, 2000; Dairy One, 2017).

For milk P content, a standard value of 0.1% P was used (Knowlton and Herbein, 2002). For manure and litter P concentrations, the most recent lab analysis from the producer was used, which occurred for 20% of the farms. Otherwise, standard average values were used from the Virginia Nutrient Management Handbook (VA DCR, 2014).

P Balance Calculations and Data Analysis

Amounts and P concentrations of imports and exports were put into a P balance calculator we built in Microsoft Excel. The spreadsheet had sections for each category of import and export, and used lookup tables to supply information such as the average P content per unit, manure and litter production rates, and average manure and litter P values. These tables were populated using data from various sources including the Virginia Nutrient Management Handbook, Dairy One, and the Nebraska whole-farm nutrient balance spreadsheet. As mentioned above, P content values from the lookup tables were replaced with values from a farmer's own analysis records as often as records were available. All calculations were performed on an as-used/as-fed basis.

For each item in each category of the spreadsheet calculator, the total annual mass of an item was multiplied by the respective P concentration. The resulting annual P mass values returned from the calculator were copied to a master dataset of all participating farms for data analysis.

Derivative variables (e.g. animal units, P balance per land base, etc.) were calculated on-the-fly with code scripts during statistical analyses. One animal unit (AU) was defined as 454 kg (1000 lbs) of live weight, such that one typical Holstein cow equaled 1.4 AU. Beef cattle were included in the AU calculation, but poultry birds were not. In the case of a mixed-operation dairy and poultry farm that exported all generated poultry litter, the birds in the poultry house did not add any P to the farm balance, as imported P in feed was exported as either poultry litter or in the birds. Where poultry litter was kept on-farm, the import of P in this litter was calculated on the basis of the number of birds and the most recent poultry litter analysis as described in DCR (2014).

Defining a zone of operation for P balance and P use efficiency

Defining a zone of operation around P balances can improve the guidance of Virginia dairy farms toward more sustainable and efficient nutrient management practices in the future. To define possible boundaries or guidelines for a P balance zone of operation, a quantile-based approach was followed to provide consistency and comparability with other studies(Nevens et al., 2006; Thomas et al., 2018). A guideline was set so that 75% of dairy farms fall below a certain P surplus per hectare. Because farms should not operate long term with negative P balances, another bounding guideline was set along the bottom of the zone at 0 kg-P ha-1 (Oenema et al., 2003).

Additionally, two guidelines were set so that 50% of dairy farms produced milk below either a certain P balance per Mg of milk or a P balance per animal unit. This 75-50 approach to setting guidelines was previously demonstrated in the state of New York, in a comprehensive P balance study in the eastern US against which Virginia might be compared (Cela et al., 2014).The quantile-based method was just one possible approach, offering a starting point to define guidelines for a sustainable and feasible zone of operation.

The zone of operation could be considered sustainable in that it suggests a maximum and minimum P balance per hectare (to avoid long-term soil P accumulation or depletion) and a maximum P balance per Mg of milk produced (to ensure a minimum P use efficiency). The zone of operation was considered feasible in that it provides a range of acceptable P balances and P use efficiencies. The ranges accommodate variations between dairy farms and allow flexibility in the management decisions of farmers. Farms operating with substantial P imbalances or P use inefficiencies could consider adopting management decisions of those farms operating within the zone. The zone of operation initially considered acceptable could be modified over time as more data and understanding is gained on how Virginia dairy farms manage P resources.

Statistics

Statistical summaries and analyses were performed using R 3.5+ (R Core Team, 2020). For any measured variables not normally distributed, logarithmic transformations were performed prior to regression analyses. Central to analysis was determining which farm characteristics explain the P balance on the highest 25% of farms and the P use efficiency on the 50% of farms below average efficiency. Comparison of means between two groups was performed using R and Welch's *T*-test.

Results and Discussion

Characteristics of 58 Virginia Dairy Farms

The farms sampled had dairy herd sizes ranging from 30 to 360 mature cows with a median of 108, which is close to the median of 102 cows in a similar P balance study in New York (Cela et al., 2014). Dairy farm data within the sample was slightly skewed by larger farms as reflected in greater means than medians for cow numbers, land base, and animal units (Table 1-1). However, the average herd size of 122 mature cows in this study was substantially less than average herd size of 224 mature cows reported by the Dairy Herd Improvement Association for Virginia in 2017, though small dairy farms may not be represented fully in that association (DHIA, 2017).

In Virginia, small dairy operations are not under nutrient management regulations and are defined as having fewer than 300 animal units, equivalent to 200 mature cows (VA DEQ, 2019). Of the 58 farms sampled, 49 (84%) were defined as small dairy operations. When beef cattle were included in the animal unit calculation, animal units ranged from 73 to 811 with a median of 220 AU. Total land base ranged from 21 to 648 ha with a median of 87 ha, or about 37% smaller than the median 139 ha farm in NY. All farms in the study spread manure on at least some portion of farmed land with a median of 74% land coverage annually. The animal density of the farms ranged from 0.7 to 6.7 AU ha^{-1} with a median density of 2.3 AU ha^{-1}, which was significantly greater than the median density in New York at 1.6 AU ha^{-1} (Cela et al., 2014).

Annual milk production varied widely from 3,106 to 15,687 kg cow^{-1} yr^{-1}, and the median of 11,383 kg cow^{-1} yr^{-1} was slightly greater than 10,548 kg cow^{-1} yr^{-1} in New York (estimated conversion based on an assumed 14% dry cow; originally reported as 9,072 kg cow^{-1} yr^{-1} including all mature cows). Of the 58 VA dairy farms, 6 were certified organic and these would be expected to produce less milk per cow on average than conventional dairies (Sato et al., 2005). Still, a minimum milk production of 3,106 kg cow^{-1} yr^{-1} indicates some dairies may be greatly under-producing milk which could have decreased their P use efficiency from a P balance standpoint.

Phosphorus Balance of 58 Virginia Dairy Farms

Phosphorus Imports to Dairy Farms

The greatest contributor to P imports was purchased feed, ranging from 0.5 to 72.8 kg-P ha^{-1} with a median of 18.6 kg-P ha^{-1} (Table 1-2). Poultry and dairy production overlap in VA, and the second and third greatest contributors to P imports were poultry litter generated in on-farm poultry houses, or brought in from off-farm poultry production as a fertilizer. All poultry feed comes from a feed mill, and as such when all poultry litter is exported, there is no impact from the presence of the poultry production on the farm P balance. Poultry litter P generated from imported poultry feed ranged from 0.0 to 135 kg-P ha^{-1}, while P imported with poultry litter produced on another farm ranged from 0.0 to 40.9 kg-P ha^{-1}. Twenty-two percent of dairy farms in 2017 imported poultry litter from other farms as a fertilizer option.

It is well known that using poultry litter as a nitrogen source can lead to an over-application of P to soils relative to crop uptake, with a resulting increase in soil test P (Maguire et al., 2008). In combination, total P imports ranged from 6.7 to 181 kg-P ha^{-1}, with a median of 34.8 kg-P ha^{-1} and SD of 30.2 kg-P ha^{-1}. The greatest variations in farm P imports were in feed imports (SD = 17.6 kg-P ha^{-1}), poultry litter generated (SD of 26.6 kg-P ha^{-1}) and poultry litter imported (SD = 8.4 kg-P ha^{-1}). Other components of P imports included bedding materials, fertilizer, imported dairy manure, and animals purchased for addition to the herd. Even combined, however, these components represented a minor portion of the overall P balance calculation, with all of these having a mean below 1 kg-P ha^{-1}.

Phosphorus Exports from Dairy Farms

The majority of P exported from dairy farms tended to be comprised of milk sold, especially in the case of farms with no poultry litter generated (Table 1-2). On a per area basis, exported P in milk ranged from 2.1 to 36.3 kg-P ha^{-1}, with a median of 10.6 kg-P ha^{-1}, which reflects differences in land base and animal densities. A study of P balance on Irish dairies also showed a significant correlation between milk output and P exports (R^2 =0.69) (Ruane et al., 2014).

Some farms with poultry operations or more crop land exported significant amounts of P through poultry litter and crop exports (Table 1-2). Poultry litter P exports ranged from 0 to 135 kg-P ha^{-1}, and farms exporting generated litter were responsible for the wide standard deviation in total P exports (SD = 26.5 kg-P ha^{-1}). Of the 14 dairy farms with poultry operations, 29% exported all generated poultry litter. On average, however, the 14 farms exported only 52% of generated poultry litter. This was lower than a state-wide assessment which found that 85% of all poultry litter generated is exported from poultry farms, according to their nutrient management plans (DCR, personal communication).

Almost half of the farms (n=26) in 2017 exported crops. Within those farms, P exports by crops ranged from 0.63 to 26.6 kg-P ha^{-1} with a median of 3.5 kg-P ha^{-1}. Of the farms with at least 100 ha of land base (n = 24), 63% exported crops, while only 32% of farms <100 ha exported crops. For all farms that exported crops, the amount of P exported (kg-P) correlated with land base (ha) (R^2 = 0.60).

Animals exported included cull cows, bull calves, and steers. The P exported through these sold animals ranged from 0.5 to 5.9 kg-P ha^{-1} with a median of 1.8 kg-P ha^{-1}. Farms with more animal units had more P exported with animals ($R^2 = 0.65$). Mixed-operation dairy and beef farms tended to have the highest values of animal P export and skewed the mean higher than the median.

Dairy manure P exports ranged from 0 to 27.2 kg-P ha^{-1} with a median of 0 kg-P ha^{-1}. Only 20.7% of farms exported dairy manure, either as liquid slurry or composted bedded pack. Dairy manure as a liquid slurry is particularly difficult to export due to the transportation expense associated with the high water content (Kleinman et al., 2012). Likewise, in an area with a high density of dairy farms such as the Shenandoah Valley of Virginia, the supply of manure may exceed the demand, requiring creative logistics for exporting (Sharara et al., 2017).

Total Phosphorus Balance for Dairy Farms

The difference between all P imports and P exports is the P balance, and the P balance on 58 VA dairy farms ranged from -30.9 to 97.6 kg-P ha^{-1} with a median of 12.4 kg-P ha^{-1} (Table 1-2). This median was comparable to the P surplus on 38 Danish dairies over multiple years which had a weighted average of 12.9 kg-P ha^{-1} (Nielsen and Kristensen, 2005). The majority of farms (79%) had a P surplus or balance greater than 0 kg-P ha^{-1}, while the remaining farms (21%) had a P balance less than 0 kg-P ha^{-1}. Those farms with P surplus need to keep track of soil test P as positive balances cause increases in soil test P that can lead to long term problems (Maguire et al., 2009).

Previous research showed that among soil types typical of the region from which our farms were sampled, Mehlich 1 soil test P concentrations tended to increase on average by 1 mg

kg^{-1} for every 9 kg-P ha^{-1} added through poultry litter applications (Maguire et al., 2008). As the median farm in our study had a P balance of 12.4 kg-P ha^{-1}, Mehlich 1 soil test P concentrations could increase by at least 1 mg kg^{-1} per year for half of the farms, assuming that the 2017 P balance is observed annually for multiple years. For farms with a P shortage, continued decreases in soil test P may be desirable so long as soil test P concentrations are above agronomic recommendations, which in VA is 55 mg kg^{-1} Mehlich 1 P (Maguire and Heckendorn, 2017).

Relationship Between Phosphorus Balance and Milk Production

As described in the methods section, we established a sustainable zone (shaded region; Fig 1-1) for which the majority of dairy farms in Virginia should be able to manage P efficiently. The P balance limit under which 75% of farms operated was 18.7 kg-P ha^{-1}, compared to 13 kg ha^{-1} in NY (Cela et al., 2014; Fig. 1.1). For soils typical of the region from which these dairy farms were sampled, a recurring annual farm P balance of at least 9 kg-P ha^{-1} tends to raise the Mehlich 1 soil test P (M1P) concentration by 1 mg kg^{-1} per year on average (Maguire et al., 2008). Therefore, setting a percentile-based P balance limit for this region of 18.7 kg-P ha^{-1} would still allow for M1P to increase by up to about 2 mg kg^{-1} annually. At M1P levels above 55 mg kg^{-1}, no further P fertilizer is recommended for most crops (Maguire and Heckendorn, 2017). Decreases in P surplus lead to decreases in excessive buildup in soil test P. For example, Ruane et al. (2014) found that P balances on 21 Irish dairy farms over four years positively correlated with soil test P concentrations ($R^2 = 0.34$).

The slope of the P use efficiency line in Fig. 1.1A was 1.0 kg-P Mg-milk^{-1}, indicating the median efficiency-by-product for which 50 percent of farms operated above and below. The efficiency level was comparable to the reported 1.1 kg-P Mg-milk^{-1} in NY (Cela et al., 2014), indicating that even in the presence of poultry litter, efficiency targets based on milk production were similar. These two guidelines show as boundaries for the P balance zone of operation in Fig. 1.1A. There was no correlation between P balance (kg-P ha^{-1}) and milk production (Mg-milk ha^{-1}) ($R^2 < 0.01$; Fig 1-1A). The absence of correlation demonstrates the potential for producers to maintain milk production while decreasing P balance and improving P use efficiency.

Impact of Dairy Farm Diversity

Virginia dairy farms are diverse in that they sometimes overlap with other animal operations. To evaluate how this diversity affected P balance, farms were grouped by operations into a) dairy only (D), b) dairy and beef (DB), c) dairy, beef and poultry (DBP), and d) dairy and poultry (DP). Among different types of farms, patterns in P balance and P use efficiency were observed.

Milk Production

The median for milk production on all farms was 10.6 Mg-milk ha^{-1} (Table 1-1). Farms with beef cattle (n = 11) had a median land base of 222 ha, or 153 ha greater than that for non-beef farms (n = 47). As beef production involves more land and does not count toward milk exports, dairy and beef (DB) farms (median 5.1 Mg-milk ha^{-1}) and dairy, beef, and poultry (DBP) farms (median 5.6 Mg-milk ha^{-1}) had lower milk production per ha. While dairy-only (D) farms (median 13.3Mg-milk ha^{-1}) and dairy and poultry (DP) farms (median 16.5 Mg-milk ha^{-1}) had greater milk production per ha.

Phosphorus Balance

For all dairy farms, the median P balance was 12.4 kg-P ha^{-1} (Table 1-2). For mixed-operation dairy farms with beef cattle (DB and DBP, n = 11), 9 had P balances below the 75th percentile (Fig. 1.1A). This clustering was observed for two reasons. Unlike dairy and poultry operations which, generally, rely largely or entirely on imported feed, beef operations tend to be grazing-based systems with low P inputs from feed. Secondly, farms with beef herds tend to be larger in area to support pastures for grazing. Larger land bases bring down the values of farm P balance and milk production as these are normalized on a per area basis.

For the 8 mixed-operation dairy and poultry farms (DP; Fig 1-1A), P balance ranged widely from 10.3 to 97.6 kg-P ha^{-1} with a median P balance of 26.3 kg-P ha^{-1}. This median P balance was significantly greater than that for all 58 farms (median = 12.4 kg ha^{-1}), but also much greater than those mixed-operation dairy and poultry farms with beef (DBP, median = 14.1 kg ha^{-1}). The DBP farms had 3.4 times more land (median = 243 ha) on average than those DP farms without beef (median = 71 ha). Dairy farms with poultry (DP and DBP) that did not export poultry litter to balance P imports fell above the 75th percentile P balance limit (n = 5). Other DP farms were able to export all generated poultry litter, and as such did not have excessive P surpluses in 2017.

Case Study

Two farms have been highlighted in Fig 1-1A as a case study. The farm with high P balance (H) is a mixed-operation dairy farm with poultry production just like the farm with low P balance (L). Both farms have similar land base, dairy herd size, and milk production, in addition to both having poultry production. However, despite these similarities, Farm H had a P surplus of

97.6 kg-P ha^{-1} while Farm L had a negative P balance of -10.3 kg-P ha^{-1}. There were several reasons for this. First, Farm H had twice as many birds as Farm L, and did not export any litter generated. Farm L exported all generated litter, in addition to exporting some dairy manure, whereas Farm H exported no dairy manure. Despite having similar land base and animal densities, Farm H imported twice as much P through purchased feed, while Farm L appeared to grow a larger proportion of their own feed. In addition, Farm L was able to export P through crops sold from the farm.

Comparing the two mixed-operation dairy and poultry farms primarily shows the importance of managing P balance from the export side. Farms like Farm H may, however, be limited in manure and litter export options based on geographic location and transportation costs (Paudel et al., 2009). Proximity to buyers or receivers of animal waste products can be important, as can the market demand for nutrients supplied in such products (Kleinman et al., 2012). Maximizing home-grown feed and limiting excessive P imports in purchased feed also helps avoid P surplus.

Relationship Between Phosphorus Balance and Animal Density

The slope of the P use efficiency line in Fig. 1.1B was 5.6 kg-P AU^{-1}, indicating the median efficiency-by-head for which 50 percent of farms operated above and below. The median efficiency was comparable to that reported in NY, or 5.4 kg-P AU^{-1} (Cela et al., 2014). With the P balance limit at 18.7 kg-P ha^{-1}, these two guidelines set the upper limits for sustainable P nutrient management in Fig. 1.1B. Considering the various farm types, dairy-only farms (D) had median P use efficiencies below that for all farms at 3.9 kg-P AU^{-1}. The median P use efficiencies by animal units for mixed-operation dairy farms (DB, DBP, and DP) were higher than for all farms combined, at 7.3, 8.05, and 11.6 kg-P AU^{-1}, respectively. Mixed-operation dairy farms with poultry also had the highest recorded inefficiencies at 37.8 kg-P AU^{-1} for DBP farms and 30.7 kg-P AU^{-1} for DP farms.

As mentioned previously, the animal density of the dairy farms ranged from 0.65 to 6.7 AU ha^{-1} with a median density of 2.3 AU ha^{-1}. Cela et al. (2014) suggested that an animal density greater than 2.4 AU ha^{-1} could be a risk factor for excessive farm P balance unless farms actively exported manure. Animal density does not appear to be a risk factor for Virginia dairy farms as there was no significant correlation between P balance and animal density ($R^2 < 0.01$; Fig 1-1B). A similar lack of correlation between P surplus and “stocking density” was also presented by Ruane et al. (2014) on 21 Irish dairy farms.

Relationship Between Phosphorus Balance, Milk Production, and Farm Factors

Land application of poultry litter

Of the 58 dairy farms studied, 22 farms (38%) land applied poultry litter that was either imported or generated on-farm (Fig 1-2A). Of the 15 farms in the highest quartile for P balance (kg-P ha^{-1}), 10 land applied poultry litter. Litter using farms had a mean P balance of 23.4 kg-P ha^{-1} compared to 6.0 kg-P ha^{-1} for all other farms, or a difference of 17.4 kg-P imported annually per hectare ($p = 0.004$). In terms of P use efficiency, 19 out of 29 farms with below average P use efficiency applied poultry litter. Litter using farms have a mean efficiency of 3.1 kg-P $Mg\text{-}milk^{-1}$ compared to all other farms which had a mean P use efficiency or 0.62 kg-P $Mg\text{-}milk^{-1}$, or 2.48 kg-P more efficient per Mg of milk produced ($p = 0.001$). Poultry litter has been shown to be a useful fertilizer, but due to its N:P ratio, it over applies P relative to crop N needs (McGrath et al., 2010). This high P content of poultry litter helps explain why land application of poultry litter was the largest risk factor for high P balance in this study.

Three dairy farms that used poultry litter managed to do so while operating below the P balance limit and above average efficiency per milk produced. In exploring these farms, large land base and crop exports stood out as key factors. Two farms were dairy-only and the other a mixed-operation dairy and beef farm. The mean land base was 336 ha with a mean animal density of 2.1 AU ha^{-1}. With larger land bases, each farm grew surplus crops, exporting on average 11.1 kg-P ha^{-1} through crops alone. For one farm, 21 kg-P ha^{-1} worth of dairy manure was also exported, thus offsetting P imports through feed and litter. These results highlight the importance of exporting poultry litter from farms with P surplus. In an agricultural region with higher animal farm density, shipping distances may increase along with transportation costs in order to sell or give away manure to a farm without P surplus.

Certified Organic Dairies

Six certified organic dairy farms participated in the study. Only one farm had a P balance greater than the 75th percentile P balance guideline. Five organic dairy farms had P use efficiencies (kg-P $Mg\text{-}milk^{-1}$) higher—or worse — than the median P use efficiency (Fig 1-2B). This occurred in part because organic dairy farms generally produce less milk per cow than conventional dairy farms due to organic program and feeding requirements (Sato et al., 2005). The higher P balances and P use inefficiencies were mostly due to importing poultry litter as an organic source of nitrogen fertilizer. Out of the 6 farms, 5 imported poultry litter for fertilizer use. Phosphorus imported with poultry litter constituted, on average, 62% of P imports (kg-P ha^{-1}) for organic dairy farms, while accounting for 97% of imported P on one farm.

Dried Distillers Grains

Dried distiller's grains (DDGs) are a common dairy feed ingredient that comes from ethanol plants and breweries, and it is a high concentration P feed as much of the carbohydrate has been removed from the feedstock. Of the 58 farms, 7 included DDG in the dairy feed rations, but only two of these had P balances in the highest quartile (Fig 1-2C). As 5 of the 7 farms were below the 75-percentile horizontal line, it appears that using DDGs is not a risk factor for excessive P balance. For the 2 farms above the P balance threshold, the main factors were use of poultry litter for the highest P balance farm and limited land base for the lower of these two farms. In comparison, 4 of the 7 farms that imported DDGs had less than average P use efficiency (kg-P Mg-milk^{-1}). Total mixed rations that include high P feed components should be carefully balanced as any excess P in the diet will end up as land-applied manure (Dou et al., 2003). For these 4 farms, the inclusion of DDGs in the total mixed ration may have contributed to their lower P use efficiency.

Feed-imported P per animal

The amount of P imported through purchased feed on a per animal unit basis was calculated in order to understand the relationship with feed imports on P balance (Fig 1-2D). Feed-imported P per AU explained 10 percent of the variability in P balance per ha ($p = 0.014$), with P balance increasing on average by 1.66 kg-P ha^{-1} for every 1 kg increase in P imported with feed purchased. For the 58 Virginia dairy farms, P imported with purchased feed ranged from 0.46 to 72.7 kg-P AU^{-1} with a median of 18.6 kg-P AU^{-1}. As mentioned previously, P imported with feed purchases constituted the largest proportion of import P in the farm-gate P balances, which has been shown in other nutrient balance studies (Gourley et al., 2012). Dairy farms can limit P imported with purchased feed in two ways. One, farms can grow a higher proportion of their own feed. Two, only purchase feed with optimal P that can be balanced into the total mixed ration without leaving an excess to be excreted in manure (Knowlton and Herbein, 2002; Dou et al., 2002). As imported feed was the biggest contributor to total farm P imports and was significantly correlated to overall farm P balance, high imports of P in feed is an obvious risk factor for excessive farm P balance.

Conclusions

The lack of a relationship between milk production and farm P balance demonstrated that some Virginia dairy farmers efficiently managed P on their farms for long term sustainability while others did not. Although there was substantial diversity between the dairy farms studied, two risk factors emerged for excessive P balance: using poultry litter and importing excessive P through purchased feeds. There is a strong local market for poultry litter, so dairy farms that include poultry production do not necessarily need to use the poultry litter they produce as a fertilizer. Comparing similar sized dairy farms showed that some dairy farms could grow most of their feed while others imported a substantial amount. The reasons for this were not clear from the data collected, but addressing this variation seems like a logical next step.

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Tables and Figures

Table 1-1. Descriptive statistics of selected characteristics for the 58 dairy, dairy and beef, dairy and poultry, and dairy, beef, and poultry farms surveyed for 2017 in Virginia.

	All farms (n = 58)						
Characteristic	Mean	Min	Q1	Median	Q3	Max	SD
Mature dairy cows (n)	122	30	81	108	148	360	63
Animal units (AU)	251	73	163	226	269	811	153
Total land base (ha)	130	21	48	87	147	648	134
Manured land (%)	69	7	51	74	91	100	25
Animal density* (AU ha^{-1})	2.8	0.7	1.5	2.3	4.1	6.7	1.6
Milk sold (kg cow^{-1} yr^{-1})	11,076	3,106	10,007	11,383	12,663	15,687	2,680
Milk sold (Mg ha^{-1})	13.8	2.1	6.2	10.6	20	36.3	9.1

* 1 Animal Unit = 454 kg animal weight (does not include poultry)

Table 1-2. Distribution of P imported onto and exported from 58 dairy and mixed-operation dairy farms in Virginia for 2017, separated into constituent parts.

	All farms (n = 58)						
Characteristic	Mean	Min	Q1	Median	Q3	Max	SD
Imports, kg-P ha^{-1}							
Feed	23.7	0.5	11	18.6	37.1	72.8	17.6
Litter, generated	12.1	0.0	0.0	0.0	0.0	135	26.6
Litter, imported	3.8	0.0	0.0	0.0	0.0	40.9	8.4
Misc, bedding	0.7	0.0	0.1	0.3	0.9	6.1	1.0
Fertilizer	0.4	0.0	0.0	0.0	0.0	10.6	1.6
Dairy manure	0.1	0.0	0.0	0.0	0.0	5.4	0.7
Animals purchased	0.1	0.0	0.0	0.0	0.1	1.6	0.3
Total	40.8	6.7	20.9	34.8	51.8	180.8	30.2
Exports, kg-P ha^{-1}							
Milk	13.9	2.1	6.2	10.6	20.0	36.3	9.2
Poultry litter	7.2	0.0	0.0	0.0	0.0	135	21.7
Crop	2.3	0.0	0.0	0.0	2.9	26.6	4.5
Animals sold	2.2	0.5	1.2	1.8	3.0	5.9	1.4
Dairy manure	2.5	0.0	0.0	0.0	0.0	27.2	6.2
Total	28.1	2.7	10.9	20.2	38.5	166.8	26.5
Total P Balance, kg-P ha^{-1}	12.6	-30.9	1.5	12.4	18.7	97.6	20.0

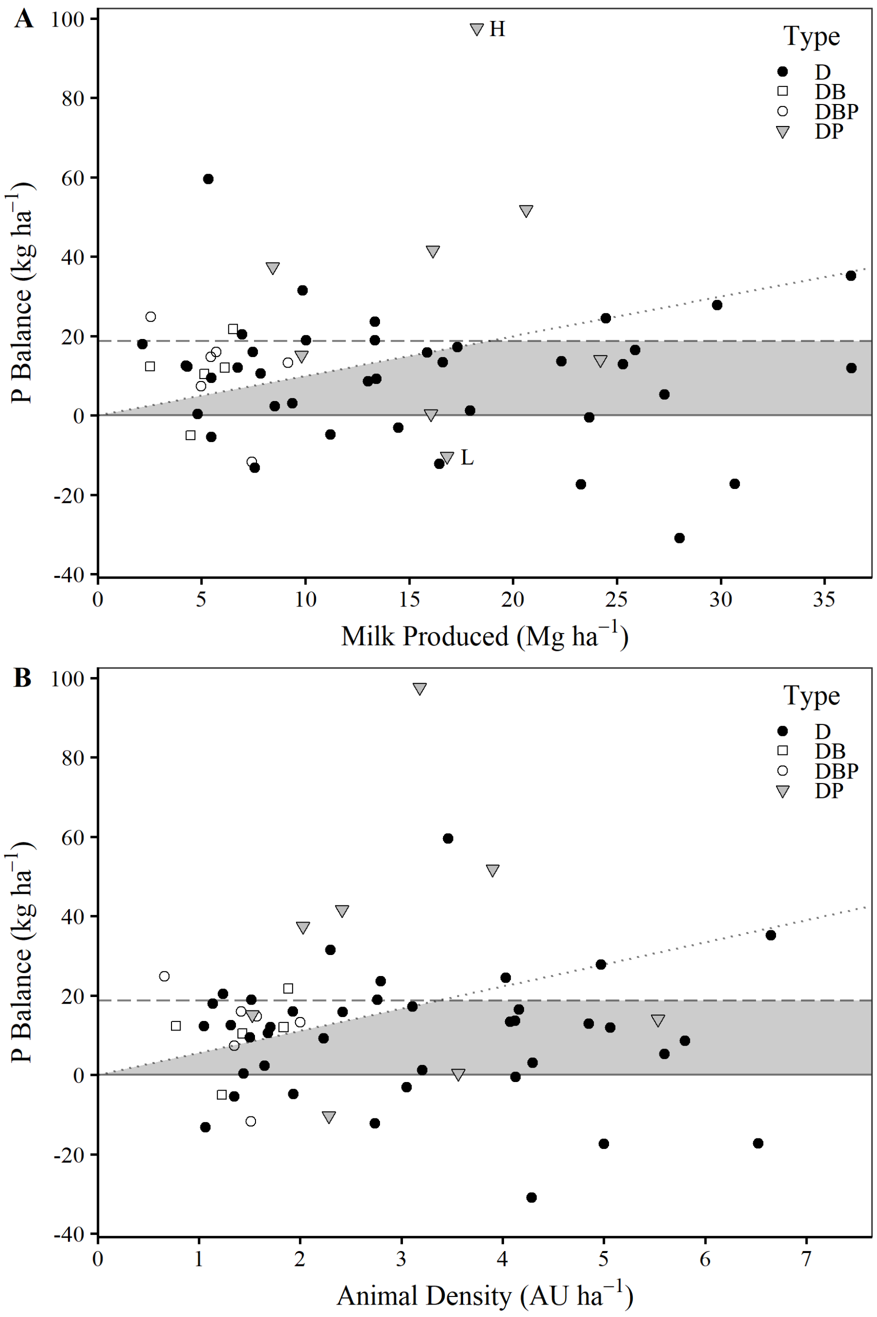

Figure 1-1. Each point represents one of the 58 Virginia dairy and mixed dairy farms in 2017. Farm types are: D = dairy operations, DB = mixed operations of dairy and beef, DBP = mixed operations of dairy, poultry, and beef, and DP = mixed operations of dairy and poultry. The shaded region bound by the three lines represents the P balance zone of operation for minimized P balance and efficient P use. **Plot A.** P balance (kg ha^{-1}) is compared to milk production intensity (Mg ha^{-1}). Two farms with similar characteristics have been marked ‘H’ and ‘L’ for their high and low P balances, and are discussed in the case study. **Plot B.** P balance (kg ha^{-1}) is compared to animal density (AU ha^{-1}), in which 1 AU = 454 kg of animal weight.

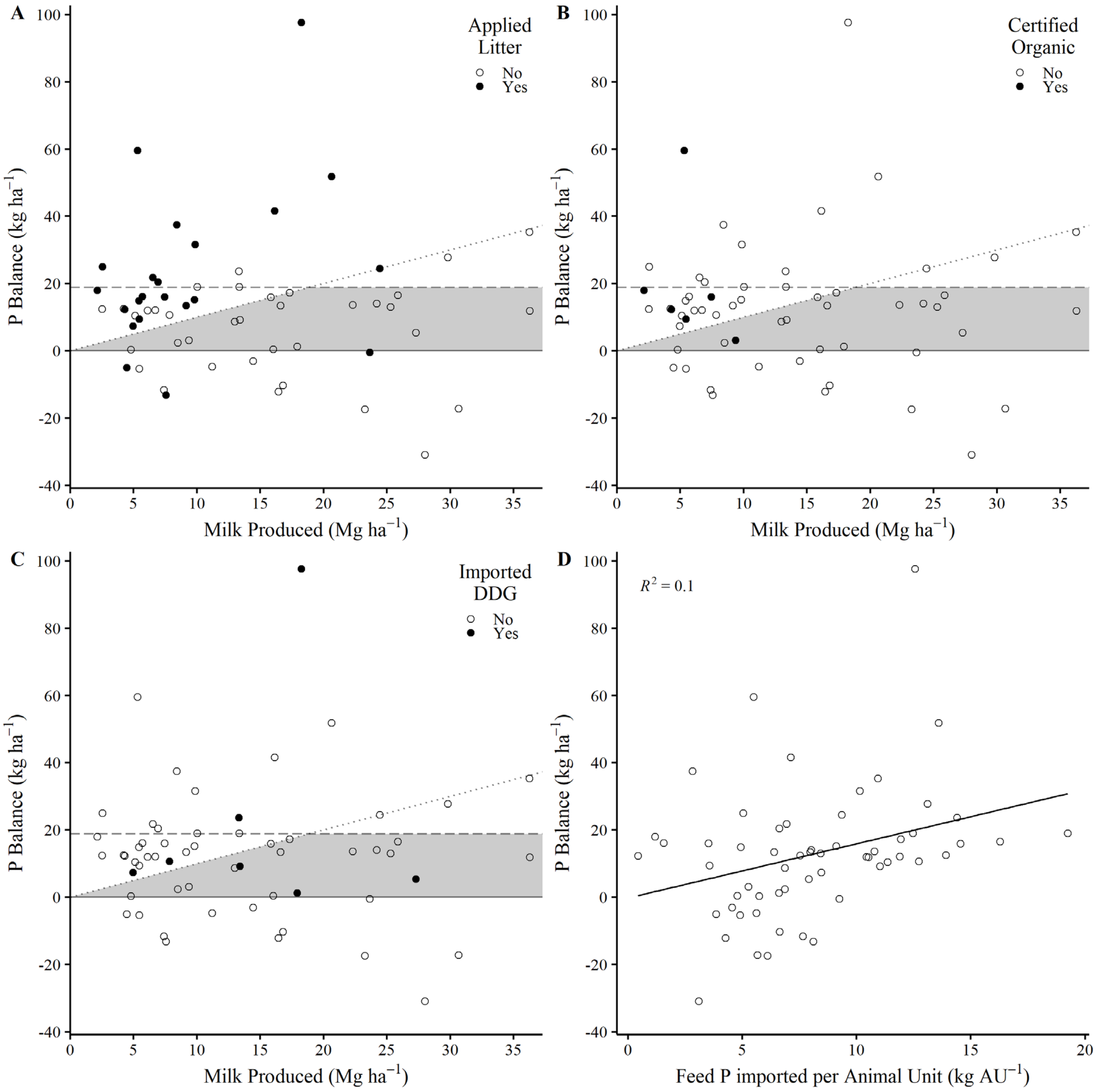

Figure 1-2. In plots A-C, P balance (kg ha^{-1}) is compared to milk production intensity (Mg ha^{-1}) for 58 Virginia dairy and mixed dairy farms in 2017. The shaded region bound by the three lines represents the P balance zone of operation for minimized P balance and efficient P use. **Plot A.** Dairy farms with a net import of poultry litter (n = 22) are highlighted. **Plot B.** The subset of certified organic dairy farms (n = 6) are highlighted. **Plot C.** Highlighted are dairy farms that imported dried distillers grain (DDG, n = 7). **Plot D**. The correlation between P balance and P imported with purchased feed per AU ($R^2 = 0.1$).

Chapter 2: Temporal changes in phosphorus balance on 30 Virginia dairy farms

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Abstract

Many dairy farms have a net positive farm phosphorus (P) balance. In the long term this inefficiency leads to P accumulation in soils, and subsequent environmental problems. An initial, farm-gate phosphorus balance assessment of Virginia dairy farms revealed certain risk factors for P surplus, but could not establish potential factors of temporal change in P balance. This study was conducted to repeat a second P balance assessment on the original participating farms, and to reveal key factors of change. Data was gathered from 30 dairy and mixed-operation dairy farms in Virginia, and compared against the initial assessment. Generally, small temporal changes were observed on the farms in terms of farm characteristics. Changes in P balances appeared to be somewhat more sensitive to total imports than total exports. Increases of 1.0 kg ha^{-1} of total P imports and exports were respectively correlated to a mean P balance increase of 0.76 kg ha^{-1} and a mean P balance decrease of 0.43 kg ha^{-1}. Changes in P imported with feed per animal unit was not significantly related to changes in P balance. Increased exports of cow manure by 1 kg P ha^{-1} was correlated to a mean decrease in P balance of 1.03 kg ha^{-1}. Mean reductions in poultry litter use by 1.06 kg P ha^{-1} was associated with a decrease in P balance of 1.00 kg ha^{-1}. The high density and overlap of dairy and poultry farms in Virginia appears to present a unique challenge to balancing P.

Introduction

Balancing phosphorus (P) is part of sustainable, efficient, and even profitable nutrient management on dairy farms (Klausner et al., 1998). Phosphorus-balanced dairy farms export as much P as is imported, which improves farm sustainability by preventing long-term soil P accumulation at the farm level. Over application of nitrogen does not result in long-term soil N accumulation, which is why the focus here is narrowed to P. Regional accumulation of soil P to concentrations beyond agronomic recommendations has been linked to animal agriculture in Canada and the United States (Maguire et al., 2007; Reid et al., 2019). Reversing the accumulation of soil P takes time, but is critical for limiting potential environmental pollution to surface waters due to agricultural runoff and soil erosion (McCollum, 1991; Sharpley and Withers, 1994). Balancing P among dairy farms in areas such as the Shenandoah Valley of Virginia will ultimately reduce nutrient loads to the Chesapeake Bay Watershed.

Balancing P on a dairy farm first requires an initial P mass balance assessment, calculated as the difference between the mass of P imported and exported through the farm gate, and divided by land area or some unit of production (Koelsch, 2005). A positive or surplus P balance per tillable hectare suggests that soil test P concentrations at the dairy farm level may become elevated over time. Drawdowns of soil P would result from a negative P balance over time, which could be acceptable in the short term if soil test P concentrations are elevated beyond agronomic recommendations (Oenema et al., 2003).

One-time, single year measurements of nutrient mass balance can provide a unique group of dairy farms with a performance base for their nutrient balance and nutrient use efficiency (Cela et al., 2015a). From the distribution of P balances, feasible benchmarks can be developed to guide any dairy farms that operate in the higher quartiles of P balance toward more sustainable ends (Cela et al., 2017; Pearce and Maguire, 2020). In addition, management factors can be identified that increase the risk of P surplus, such as oversupplying P in feed or securing adequate land for forage production (Cela et al., 2014).

Tracking P Balance

Snapshot P balances cannot, however, suggest trends in the long-term sustainability of a farm. Subsequent P balance assessments are necessary to track temporal changes in P balance and to determine key factors of any observed change. While drastic changes in herd size, cropland, and ration formulations may be unlikely from one year to the next, some annual variation in nutrient balances can be reasonably expected, due perhaps to fluctuations in crop yields, herd dynamics, or market prices (Cela et al., 2015a).

Previous research has demonstrated the importance of repeated P balance assessments. In Ireland, 21 dairy farms were tracked for 3 years, and it was found that the mean P imported with feed varied significantly over the years (Mihailescu et al., 2015). On the other hand, a three-year study of 138 dairy farms in Sweden found that P balance varied "little" over time, though it failed to report actual values of temporal variation (Swensson, 2003). In a study of 54 dairy farms in New York state, reductions in P balance over time were tied to improved precision feeding and reducing total nutrient imports, as well as increasing manure exports on farms with higher animal densities (Soberon et al., 2015). Over time, P balance tracking can guide farms toward lower, more sustainable nutrient balances (Cela et al., 2017).

An assessment of P balance on 58 dairy and mixed-operation dairy farms in Virginia in 2017 reported considerable variation in P balance between farms (Pearce and Maguire, 2020). This was due to a wide variety of factors including variation in P use efficiency per unit milk production, increased P imported with feed per animal unit, and the use of poultry litter as a fertilizer. After the initial assessment, individualized reports were given to each farmer. This feedback informed them of their current farm P balance status relative to the other farms involved as well as potential risk factors that may have caused elevated P balances. Similar information on farm P mass balance and risk factors (in addition to focused education and regulatory efforts) has led to decreased P balances elsewhere (Ruane et al., 2014; Cela et al., 2017). Unique still to Virginia is the overlap of poultry and dairy production, and how sensitive P balance is to changes in poultry litter use. Therefore, the objectives of this study were to: 1) perform a subsequent P mass balance assessment for participating dairy farms in Virginia after the first round of assessment and farmer education, and 2) reveal factors to which P balance is sensitive to change.

Materials and Methods

Sampling and Data Collection

Our initial P balance assessment was conducted in 2017 on 58 Virginia dairy farms (Pearce and Maguire, 2020). After the initial assessment, individualized reports were returned to each farmer which included a comparison to the whole group. Farms were then invited to participate for a second year. Of the original 58 farms, 30 resubmitted data necessary to calculate a second P balance in 2018. Farmers seemed generally more familiar with the data collection process the second year, and had an easier time participating and updating their information. Data were usually collected during on-farm visits, but collection sometimes was also conducted over the phone for a farmer's convenience. The sample was composed of mostly small, unregulated dairy farms, which in Virginia are those with less than 200 mature cows, and are not required to have a nutrient management plan (VA DEQ, 2019). Eleven of farms were mixed operations having beef and/or poultry enterprises in addition to the dairies.

The P balance assessment accounted for all P imports and exports that passed through farm gates between January 1 and December 31 of 2018. Detailed description of the data collection process can be found in Pearce and Maguire (2020). Briefly, for all farms data was collected on feed purchased, fertilizers, animal manure, imported poultry litter, animals purchased, and bedding materials to calculate P imports. Exports were milk sold, animals sold, crops sold, and animal manures exported off-farm. Other information collected included tillable land area, including rented land, animal numbers and sizes, and organic production.

Mixed-operation dairy farms with poultry production generate poultry litter. This generated litter was also accounted for in the P balance calculations, both as an import and export. A distinction was made between generated poultry litter and deliberately imported poultry litter, as the former can be exported. In the case that a mixed dairy and poultry farm retained a portion of generated poultry litter for land application, the P imported or exported was calculated based on the number of birds and the most recent litter analysis, as describe in DCR (2014). If a mixed dairy and poultry farm exported 100% of generated poultry litter, then poultry production ultimately had no impact on farm P mass balance.

Data collection required getting the total annual amounts of items as well as the P concentrations of the items. If farmers could not readily provide an acceptable P analysis on a feed item, efforts were made to contact nutritionists or to make reasonable estimates using standard databases such as DairyOne or book values from the Nutrient Requirements of Dairy Cattle (NRC, 2000; Dairy One, 2017). If a farmer did not have an up-to-date analysis of dairy manure or poultry litter, average book values for these manures were used (VA DCR, 2014). A standard value of 0.1% P was used for milk produced as previously documented (Knowlton and Herbein, 2002).

P Balance Calculations and Data Analysis

The spreadsheet used for P mass calculations was described in (Pearce and Maguire, 2020). The mass of P for an item was calculated as the product of the total annual quantity of the item and the P content of the item. Phosphorus balance was calculated as the difference between the sum of P imports and the sum of P exports. Derivative variables such as P balance per hectare were calculated automatically during analysis using scripts. For derivative variables relating to animal density, an animal unit (AU) was defined as 454 kg (1000 lbs) of live weight, with a typical Holstein mature cow equaling 1.4 AU. Milk per cow was based on milking cow numbers, and not all mature cows. Results for 2018 were analyzed in the context of benchmarks set in 2017, which put an upper limit P balance of 18.7 kg ha^{-1} feasible for 75% of initial farms, and a lower limit P use efficiency of 1.0 kg Mg-milk^{-1} feasible for 50% of initial farms (Pearce and Maguire, 2020). In order to assess temporal variation, change variables were calculated by subtracting final values (2018) from initial values (2017) for all variables.

Statistics

Statistical summaries and ordinary least squares regressions were conducted within an R 3.6+ environment (R Core Team, 2020). Regressions were analyzed for significance at the $\alpha = 0.05$ level. Multiple regression analyses were not usually possible as the sum of input variables created the output variable of P balance, which violates assumptions of independence.

Correlation between change variables were interpreted as how sensitive change in one variable was to change in another. If a change of 1.0 kg ha^{-1} of some variable correlates to a change greater than 1.0 kg ha^{-1} in the outcome variable, the relationship should be viewed in terms of sensitivity. Where pertinent, analyses were conducted with and without any farms that strongly influenced the regression models or interpretations thereof. Any outlying or influential farms were not excluded outright from all analysis in an effort to more completely understand P balance management among Virginia dairy farms. Analyses were also conducted on subsets of farms where relevant. For example, assessing the relationship between changes in P exported with crops and changes in P balance may yield different conclusions for all farms than for the subset that exported crops both years.

Results and Discussion

Initial Farm Characteristics and Change between 2017 and 2018

Of the 30 dairy farms that participated in 2017 and 2018, 19 were dairy-only farms during both years, six were mixed operations of dairy and poultry (one dairy farm added a poultry enterprise in the second year), two were mixed operations of dairy and beef, and the remaining three were mixed operations of dairy, beef, and poultry. In the group, 90% were classified as "small" dairy farms according the standard set for Virginia nutrient management regulation, being farms with less than 200 mature cows (VA DEQ, 2019). The number of mature cows ranged from 42 to 260, with a median herd size of 108 (Table 2-1). Mean herd size remained fairly constant over the two years, with dairy cow number changes for individual farms ranging from -15 to +40.

Tillable farm land (including rented) ranged from 21 to 567 ha, with a median size of 83 ha (Table 2-1). Farm land over the two years remained steady (mean = 1.0 ha; range -28.3 to 21.9 ha). Animal densities ranged from 1.0 to 6.5 AU ha^{-1} with a median of 2.4 AU ha^{-1}. Previous studies have recommended 2.4 AU ha^{-1} as a threshold for animal density, with farms of higher animal density at higher risk for P surplus (Cela et al., 2015b). Pearce and Maguire (2020) reported no direct link between animal density and farm P balance for Virginia dairy farms. Animal density was stable on average over the two years, decreasing at most by -2.2 AU ha^{-1} and increasing at most by 0.6 AU ha^{-1}. The decrease of -2.2 AU ha^{-1} observed was an example of a farm that simultaneous decreased herd size and acquired more land.

Milk yield per cow varied widely from 3,105 to 15,686 kg-milk cow^{-1} yr^{-1}, with a mean of 10,892 kg-milk cow^{-1} yr^{-1} (Table 2-1). Mean milk yield was skewed down due to the participation of four organic dairy farms, which expectedly produced less milk per cow than the conventional dairies (5,809 kg cow^{-1} yr^{-1} compared to 11,729 kg cow^{-1} yr^{-1}, respectively) (Sato et al., 2005). Milk production per cow increased slightly in year two (mean = 82.2 kg-milk cow^{-1} yr^{-1}; range = -719 to 1,272 kg-milk cow^{-1} yr^{-1}). Increased milk production can improve farm efficiency and increase P exports. Milk production per ha decreased slightly in year two (mean = -0.7 Mg milk ha^{-1}; range = -12.2 to 3.5 Mg-milk ha^{-1}).

On 75% of farms, at least half of the farm land received manure applications, ranging from 14.3 to 100% of land receiving manure at some point during the year, with a median of 76.4%. The mean change over the two years was small (mean = -2.7 %; range = -50 to 12.5%). Overall the relative changes in these farm characteristics were small, with the means of all factors reported in Table 2-1 changing by <6% between 2017 and 2018.

Initial Phosphorus Imports and Change from 2017 to 2018

Overall, the total P imported ranged widely in 2017 from 13.5 to 98.5 kg ha^{-1} with a median amount of 36.7 kg ha^{-1} (Table 2-2). The mean total P imported across all 30 farms remained unchanged in year two (mean = 0.0 kg ha^{-1}; range = -21.4 to 32.4 kg ha^{-1}). The three main constituents of P imported through the farm gate were feed, generated poultry litter, and imported poultry litter, making up >97% of mean P imports (Table 2-2).

Purchased feed contributed between 0.5 and 65.1 kg ha^{-1} in 2017, with a mean amount of 18.0 kg ha^{-1}. In year two, mean import of feed-P only decreased by -0.4 kg ha^{-1} (range = -15.2 to 37.3 kg ha^{-1}). Normalizing for dairy and beef animal units, the amount of P imported with feed ranged from 0.4 to 14.6 kg AU^{-1} with a mean of 7.9 kg AU^{-1}. In both years, mean P imported from feed exceeded the means reported for similar sized dairy farms in Ireland and New York, which were 7.6 and approximately 10 kg P ha^{-1}, respectively (Cela et al., 2014; Mihailescu et al., 2015). Becoming self-sufficient in homegrown feed production and reducing oversupply of P in purchased feed is important for improving farm P balance and use efficiency (Powell et al., 2002).

Of the 30 farms, initially 8 had poultry operations that generated litter, with another dairy farm adding a poultry enterprise in 2018 for a total of 9 farms. Phosphorus imported via generated poultry litter on this subset of farms ranged from 10.9 to 82.8 kg ha^{-1} in 2017, with a mean of 41.0 kg-P ha^{-1}. As the number of birds grown per year was fairly constant between years, the mean increase of P generated by poultry litter was just 2.9 kg ha^{-1}, skewed by the greatest increase of 42.1 kg ha^{-1} for the farm that introduced a poultry enterprise.

Aside from these farms with poultry production, another 7 of the 30 farms chose to import poultry litter in each year for use as fertilizer. For this second subset of farms, P from imported poultry litter in 2017 ranged from 8.8 to 40.9 kg ha^{-1} with a mean of 19.7 kg ha^{-1}. In year two, the mean amount of P from imported poultry litter decreased in 2018 by -3.7 kg P ha^{-1} (range = -29.1 to 10.4 kg ha^{-1}). The high amounts of P imported via poultry litter, either deliberately or as a by-product of poultry production, was demonstrated to be a risk factor for P surplus and P use inefficiency on Virginia dairy farms (Pearce and Maguire, 2020).

The remaining P imported through bedding, manure, fertilizer, and purchased animals typically constituted a minor portion of the total P imported, contributing 0.5 kg ha^{-1} or less on average (Table 2). Only two of the farms imported dairy manure, probably due to the high expense for transport as dairy manure is about 95% water by weight (VA DCR, 2014). As a result, the change in P imported with dairy manure ranged from -1.4 to 17.8 kg ha^{-1}.

Initial Phosphorus Exports and Change from 2017 to 2018

The total amount of P exported ranged widely from 2.7 to 72.1 kg ha^{-1}, with most of the variability due to the exports of generated poultry litter. In year two, total P exported decreased by a mean of -2.6 kg ha^{-1} as compared to year one (range = -56.8 to 31.4 kg ha^{-1}). Milk sold was the predominant P export on most dairy farms, ranging from 2.1 to 36.3 kg ha^{-1} with a mean of 13.9 kg ha^{-1} (Table 3). Overall, the mean amount of P exported with milk decreased slightly by -0.7 kg ha^{-1} (range = -12.2 to +3.5 kg ha^{-1}). Given milk P content is relatively constant (Knowlton and Herbein, 2002), changes in P exported with milk were due to fluctuations in total milk production.

Mixed-operation farms with dairy and poultry had the ability to export any generated poultry litter. Generated litter ended up being a major portion of total P exports on mixed farms that chose to export their litter. Phosphorus exported with generated poultry litter ranged from

0.0 to 53.1 kg ha^{-1} with a mean of 26.0 kg ha^{-1}. The average amount of P exported with poultry litter decreased by -4.3 kg-P ha^{-1} in year two (range = -53.1 to 37.9 kg ha^{-1}). The wide range of P exported with generated poultry litter as well as the wide range of change in litter exports reflected the annual variation in poultry litter use. The decision of whether to use poultry litter in each year depends on nitrogen needs, nutrient management plan allowances, and prices of other fertilizer options such as urea. For poultry production in Virginia, all the feed comes from a feed mill, but the poultry litter can stay on the farm or be exported. If all the poultry litter is exported from the farm, there is no impact on farm P mass balance from the poultry production as all P imported is exported (Pearce and Maguire, 2020).

Crops sold was a minor but substantial P export for 12 dairy farms exporting crops during both years. Crops sold accounted for a mean export of 5.9 kg ha^{-1} on this subset of farms. For all 30 farms, P exported with crops ranged from 0.0 to 14.3 kg ha^{-1} with a mean of 2.5 kg ha^{-1} (Table 2-3). There was little change between years on all 30 farms of mean P exported with crops sold, ranging from -2.9 to 2.4 kg ha^{-1}. The ability of a Virginia dairy farm to export crops was positively related to the size of the land base (Pearce and Maguire 2020). Crops generally account for very small proportions of P exports as observed in similar studies (Spears et al., 2003; Cela et al., 2014; Mihailescu et al., 2015).

Mean dairy manure exports (either as liquid slurry or compost bedded pack) were 2.4 kg P ha^{-1}, ranging from 0.0 to 21.1 kg-P ha^{-1}. Compared to year one, change in P exported with dairy manure ranged from -16.6 to 5.6 kg ha^{-1} with an average change of -0.4 kg ha^{-1} in year two. Opportunities to export dairy manure can be limited in areas of high animal farm density, but is nonetheless a critical factor in managing P (Kleinman et al., 2012). The amount of P exported with animals ranged from 0.5 to 5.9 kg P ha^{-1} with a mean of 2.4 kg ha^{-1}, being comprised of cull cows, calves, and beef cattle. This component of P export did not change in year two compare to year one (range = -1.5 kg P ha^{-1} to 2.0 kg-P ha^{-1}.

Initial Phosphorus Balances and Changes from 2017 to 2018

Initial P balance calculations conducted for 2017 showed that the 30 Virginia dairy farms had P balances ranging from -30.9 to 59.6 kg ha^{-1} with a mean of 12.2 kg ha^{-1} (Table 2-4). In year two, the mean P balance increase was 2.6 kg ha^{-1} (range = -11.6 to 35.4 kg ha^{-1}), skewed above the median of 0.2 kg ha^{-1} largely because one farm retained its generated poultry litter rather than exporting it as they had in 2017. Without this one farm, the mean change in P balance in year two would have been 1.5 kg ha^{-1}. Though an increase was observed in year two, determining the long term direction of a P balance trend would require continued observations over more years to come.

In other P balance studies that spanned more years, dairy farms decreased mean P balance over time, by 1.3 kg P ha^{-1} during a 3 year study in Ireland, 4 kg P ha^{-1} during a 4 to 6 year study in New York, and 2 kg P ha^{-1} over 4 years in another Irish study (Ruane et al., 2014; Mihailescu et al., 2015; Soberon et al., 2015). The success in these places may have been due to organized nutrient management initiatives that specifically targeted nutrient balance, in addition to regulatory pressures. While the Virginia dairy farms had introductory knowledge of P balance and were presented with reports after the first assessment, perhaps a long term trend toward lower P balance would emerge if farms were enrolled in a more structured initiative or program similar to those in New York or the European Union.

Initial P balance per milk produced ranged from -1.6 to 11.2 kg P Mg-$milk^{-1}$ with a mean of 1.7 kg-P Mg-$milk^{-1}$ (Table 2-4). In 2018, the mean P balance per milk produced did not change, though the greatest decrease was -4.6 kg P Mg-milk^{-1} and the greatest increase was +2.9 kg P Mg-milk^{-1}. Again, this increase of 2.9 kg-P Mg-milk^{-1} was due one farm that retained generated poultry litter. The range of P balance per animal unit (AU) was initially -7.7 to 18.4 kg-P AU^{-1} with a mean of 5.5 kg-P AU^{-1}. The mean change in 2018 was +1.0 kg-P AU^{-1}, with changes in P balance per AU ranging from -9.3 kg-P AU^{-1} to 12.7 kg-P AU^{-1}.

Change in P balance per hectare

Eight farms increased P balance by at least 2.6 kg ha^{-1}, seven farms had their P balance decrease by at least 2.6 kg ha^{-1}, and the P balance on the remaining 15 farms changed by less 2.6 kg ha^{-1} (Fig 2-1). The initial P balance assessment of 58 Virginia dairy farms suggested a feasible upper limit to P balance of 18.7 kg ha^{-1}, such that 75% of farms could operate below that target as they were (Pearce and Maguire, 2020). Between 0 and 18.7 kg ha^{-1} was defined as a sustainable zone for P balance per hectare that prevents both excessive build up and prolonged drawdown of soil test P. Of the 15 dairy farms initially in the sustainable zone in year one, 12 farms managed to remain while two additional farms reduced their P balance into the sustainable zone for year two (Fig 2-1). Three farms increased their P balance per hectare in year two above the threshold of 18.7 kg ha^{-1}. These increases were due to increased poultry litter use, and reduced manure exports coupled with small land base.

From a P balancing perspective, dairy farms with P surplus in the initial year would ideally adapt management practices to achieve a lower, more sustainable P balance over time. Otherwise, this surplus P will end up in the soil, and soil test P will keep increasing, which could lead to increased losses to the environment and bans on future use of manure due to soil test P regulatory caps (Bond et al., 2006; VA DCR, 2014). The initial P balance in 2017 for all 30 farms explained 78% of variation in the final P balance in 2018 ($r = 0.88$, $p < 0.001$). Without the one farm that had the large change in poultry litter retention it would have been even higher ($r^2 = 0.87$). The strong positive relationship reflected the relative stability in P balance across the two years. This also indicated how retention of poultry litter can have a large impact on farm P balance.

Another way to assess trends in P balance was to observe the relationship between the farms' initial P balances and the change in P balance. Ideally, farms with high P surpluses would have exhibited the greatest improvements, while farms in the sustainable zone between 0 and 18.7 kg P ha^{-1} would have maintained P balance with little change. However, there was no correlation observed across all 30 farms between initial P balance per hectare and change observed from 2017 to 2018 ($r = 0.05$).

Changes in milk production (Mg-milk cow^{-1} yr^{-1}) among these 30 Virginia dairy farms was not significantly correlated with changes in P balance ($r = 0.13$, $p = 0.49$). Similar findings have been reported previously (Soberon et al., 2015). The lack of relationship implies that changes in factors that decreased P balance did not cause decreased milk production.

Factors of Change in Phosphorus Balance

Factors among imports

An initial analysis showed that change in total imported P was not correlated with change in P balance, on a per hectare basis ($r = 0.1$, $p = 0.59$). Two farms with major changes related to poultry were highly influential to the conclusion (e.g. one added poultry production for the final P balance assessment). When excluded, change in total P imported per hectare was significantly correlated with change in P balance per hectare (Fig 2-2A; $r = 0.7$, $p < 0.001$), in which an increased import of 1.0 kg-P ha^{-1} correlated with a mean P balance increase of 0.76 kg-P ha^{-1}. As explained earlier, the main components of total P imports each year were purchased feeds, generated poultry litter, and imported poultry litter for fertilizer use.

Imported P from feed per AU was slightly correlated positively ($r = 0.3$, $p = 0.014$) with P balance per hectare on Virginia dairy farms in 2017 (Pearce and Maguire, 2020). Soberon et al. (2015) reported a significant positive relationship ($r^2 = 0.62$) between reductions in P from feed imports and reductions in P balance over time. Over the two-year period from 2017 to 2018, no significant relationship was observed between changes in P imported with feed per AU and changes in P balance (Fig 2-2B; $r^2 = 0.093$, $P = 0.10$).

Considering only the 15 farms that either generated poultry litter or that imported litter, change in P imported with any litter showed no significant relationship with change in P balance (Fig 2-2C; $r^2 = 0.086$, $P = 0.28$). This result did not account for the effect of exported litter on the P balance, which is discussed later on.

Factors among exports

The change in total P exported was significantly correlated negatively with change in P balance (Fig 2-4A; $r = -0.66$, $P < 0.001$). As total P exports increased by 1.0 kg P ha^{-1}, a mean P balance decrease of -0.48 kg P ha^{-1} was observed. This relationship was due mostly to the export of poultry litter and cow manure rather than crops (Fig. 2-3). Soberon et al. (2015) observed a weaker relationship between total P exports and P balance changes in New York ($r = -0.36$), though manure exports were likewise identified as a significant factor.

Focusing on the 9 farms that had poultry productions, an increase of 1.0 kg-P ha^{-1} of litter exported resulted in an average decrease of -0.43 kg-P ha^{-1} in P balance (Fig 2-3B; $r^2 = 0.62$, p = 0.011). This relationship does not account for imports via generated litter, which is discussed in the next section. The export of cow manure, whether as liquid slurry or bedded pack, also significantly affected P balance, and increasing exports of manure by 1.0 kg-P ha^{-1} lead to a mean decrease in P balance by 1.06 kg-P ha^{-1} (Fig 2-3D; $r^2 = 0.17$, p = 0.02). This relationship was similarly observed in NY where increasing exports of manure by 1.0 kg-P ha^{-1} decreased P balance by 1.54 kg-P ha^{-1} on average ($r^2 = 0.25$, p = 0.02). In the initial P balance assessment, crop exports were found to be related to tillable hectares (Pearce and Maguire 2020). However, in observing changes to P balance, the change in P exported with crops was not found to be a significant factor across all farms (Fig 2-3C; $r^2 = 0.029$, p = 0.36).

Poultry litter

The sensitivity of farm P balance to poultry litter was most clearly observed when comparing the change in overall P balance to the change of that fraction of P balance associated only with imported and exported litter. Change in litter-P balance (kg P ha^{-1}) ranged from -29.1 to 36.8 kg P ha^{-1} with a mean increase of 2.6 kg P ha^{-1} (Table 4). For all 15 farms that used litter at some point over the two-year period, a change in litter-P balance was correlated to change in overall P balance (r = 0.5, p = 0.057). Analysis was also conducted after excluding an outlying farm with limited land base (21 ha relative to 114.8 ha mean farm size), as that made it exceptionally sensitive to relatively small changes in P imports. The second analysis showed that changes in P balance were very sensitive to changes in litter-P balance, with an increased use of poultry litter of 1.0 kg P ha^{-1} resulting in an average increase of P balance of 1.03 kg P ha^{-1} (Fig 2-4, $r^2 = 0.9$, $p < 0.001$).

This relationship is important because the application of poultry litter as a nitrogen source brings, too, a disproportionate amount of P due to the low N:P ratio of animal manures (Maguire et al., 2009). While avoiding poultry litter use and increasing cow manure exports are straightforward recommendations, each are limited in their application in an area of high density and overlap of dairy and poultry production. The availability and cost of poultry litter as N fertilizer may deter some dairy farmers from seeking out conventional, albeit more expensive, N fertilizers when prices are favorable to poultry litter use.

Conclusion

Dairy farm P balance was relatively stable from one year to the next, with the exception of changes in the use of poultry litter. Dairy farms tended to have a positive P balance due to imports of cow feed, and use of poultry litter increased their P balance. Unlike changes in crop production and herd size which can be difficult, it is fairly straight forward for farmers to choose to use poultry litter as a fertilizer source or not. For those farms with higher P balances, avoiding the use of poultry litter would be the most straight forward strategy for decreasing their P balance. Securing adequate land for total feed production is part of limiting animal density, which in turn reduces feed imports, a contributor to P surplus. The overlap between poultry and dairy production in Virginia appears to present a unique challenge to balancing P, one not often noted in similar nutrient balance studies.

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Tables and Figures

Table 2-1. Descriptive statistics of selected characteristics for 30 dairy and mixed-operation dairy surveyed for 2017 and 2018 in Virginia.

	Initial (2017; n = 30)				Change from 2017 to 2018			
Characteristic	Min	Median	Mean	Max	Greatest decrease	Median	Mean	Greatest Increase
Farm Size								
Area (ha)	21.0	83.0	114.8	566.6	-28.3	0.0	1.0	21.9
Animal Density* (AU/ha)	1.0	2.4	2.9	6.5	-2.2	0.0	-0.1	0.6
Mature dairy cows	42.0	108.0	119.1	260.0	-15.0	0.0	1.2	40.0
Milk per cow (kg-milk/cow/yr)	3,105	11,321	10,892	15,686	-835	0.0	95.6	1,478
Milk (Mg-milk/ha)	2.1	13.2	13.9	36.3	-12.2	0.0	-0.75	3.5
Percent land manured (%)	14.3	76.4	68.7	100	-50.0	0.0	-2.7	12.5

*1 Animal Unit = 454 kg animal weight (not including poultry)

Table 2-2. Distribution of P imported onto 30 dairy and mixed-operation dairy farms in Virginia for 2017, separated into constituent parts, and the change in those parts from 2017 to 2018.

	Initial (2017; n = 30)				Change over two years			
Imported P (kg-P ha^{-1})	Min	Median	Mean	Max	Greatest decrease	Median	Mean	Greatest Increase
Feed	0.5	18.0	23.8	65.1	-15.2	0.0	-0.4	37.3
Poultry litter								
Generated*	0.0	0.0	10.9	82.8	-16.2	0.0	0.9	42.1
Imported	0.0	0.0	4.6	40.9	-29.1	0.0	-0.9	10.4
Bedding	0.0	0.2	0.5	2.3	-1.1	0.0	0.0	1.8
Dairy manure	0.0	0.0	0.2	5.4	-1.4	0.0	0.5	17.8
Fertilizer	0.0	0.0	0.2	4.5	-4.5	0.0	-0.2	0.0
New animals	0.0	0.0	0.1	1.6	-1.4	0.0	0.0	2.2
Total P Imported	13.5	36.7	40.4	98.5	-21.4	-0.2	0.0	32.4

*Values based on all dairy farms, not just the 8 mixed-operation farms with poultry production in 2017.

Table 2-3. Distribution of P exported from 30 dairy and mixed-operation dairy farms in Virginia for 2017, separated into constituent parts, and the change in those parts from 2017 to 2018.

	Initial (2017; n = 30)				Change from 2017 to 2018			
Exported P (kg-P ha^{-1})	Min	Median	Mean	Max	Greatest Decrease	Median	Mean	Greatest Increase
Milk sold	2.1	13.2	13.9	36.3	-12.2	0.0	-0.7	3.5
Generated poultry litter*	0.0	0.0	6.9	53.1	-53.1	0.0	-1.3	37.9
Crops sold	0.0	0.0	2.5	14.3	-2.9	0.0	-0.2	2.4
Dairy manure	0.0	0.0	2.4	21.1	-16.6	0.0	-0.4	5.6
Animals sold	0.5	2.0	2.4	5.9	-1.5	0.0	0.0	2.0
Total P Exported	2.7	19.9	28.2	72.1	-56.8	0.0	-2.6	31.4

*Values based on all dairy farms, not just the 8 mixed-operation farms with poultry production in 2017.

Table 2-4. Distribution of P balance metrics from 30 dairy and mixed-operation dairy farms in Virginia for 2017, provided on the basis of land base, milk produced, and animal units. The change in those balances from 2017 to 2018 is also shown.

	Initial (2017; n = 30)				Change from 2017 to 2018			
Balances	Min	Median	Mean	Max	Greatest decrease	Median	Mean	Greatest Increase
P balance (kg-P ha^{-1})	-30.9	12.1	12.2	59.6	-11.6	0.2	2.6	35.4
P balance (kg-P $Mg\text{-}milk^{-1}$)	-1.6	1.2	1.7	11.2	-4.6	0.0	0.0	2.9
P balance (kg-P AU^{-1})	-7.7	5.9	5.5	18.4	-9.3	0.1	1.0	12.7
	(n = 15)							
Litter P Balance (kg-P ha^{-1})	0.0	19.3	17.2	40.9	-29.1	0	2.6	36.8

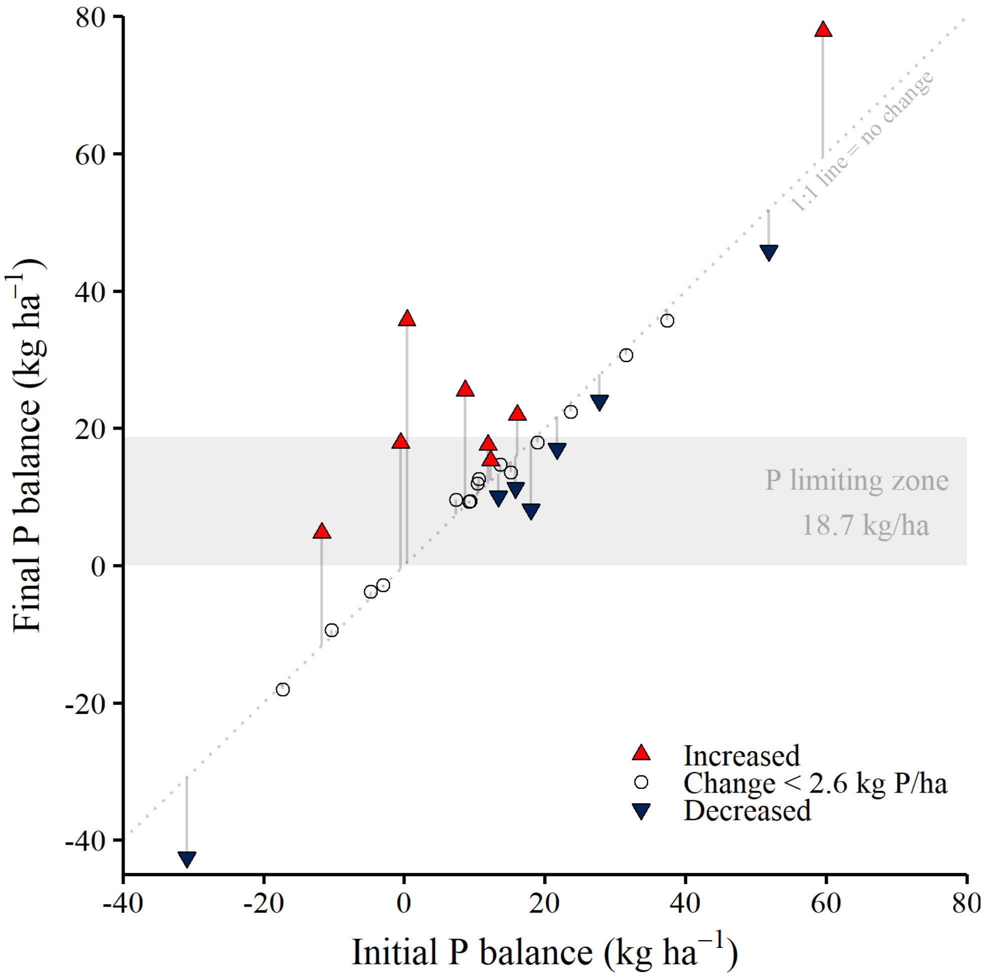

Figure 2-1. Initial P balance (kg ha^{-1}) in 2017 is compared to final P balance in 2018 for 30 dairy farms in Virginia. The farms (points) are categorized according to change in P balance: increased, decreased, or changed less than 10% from the initial to final year. The feasible zone of P balance is shown as a gray region, ranging from 0 to 18.7 kg-P ha^{-1}.

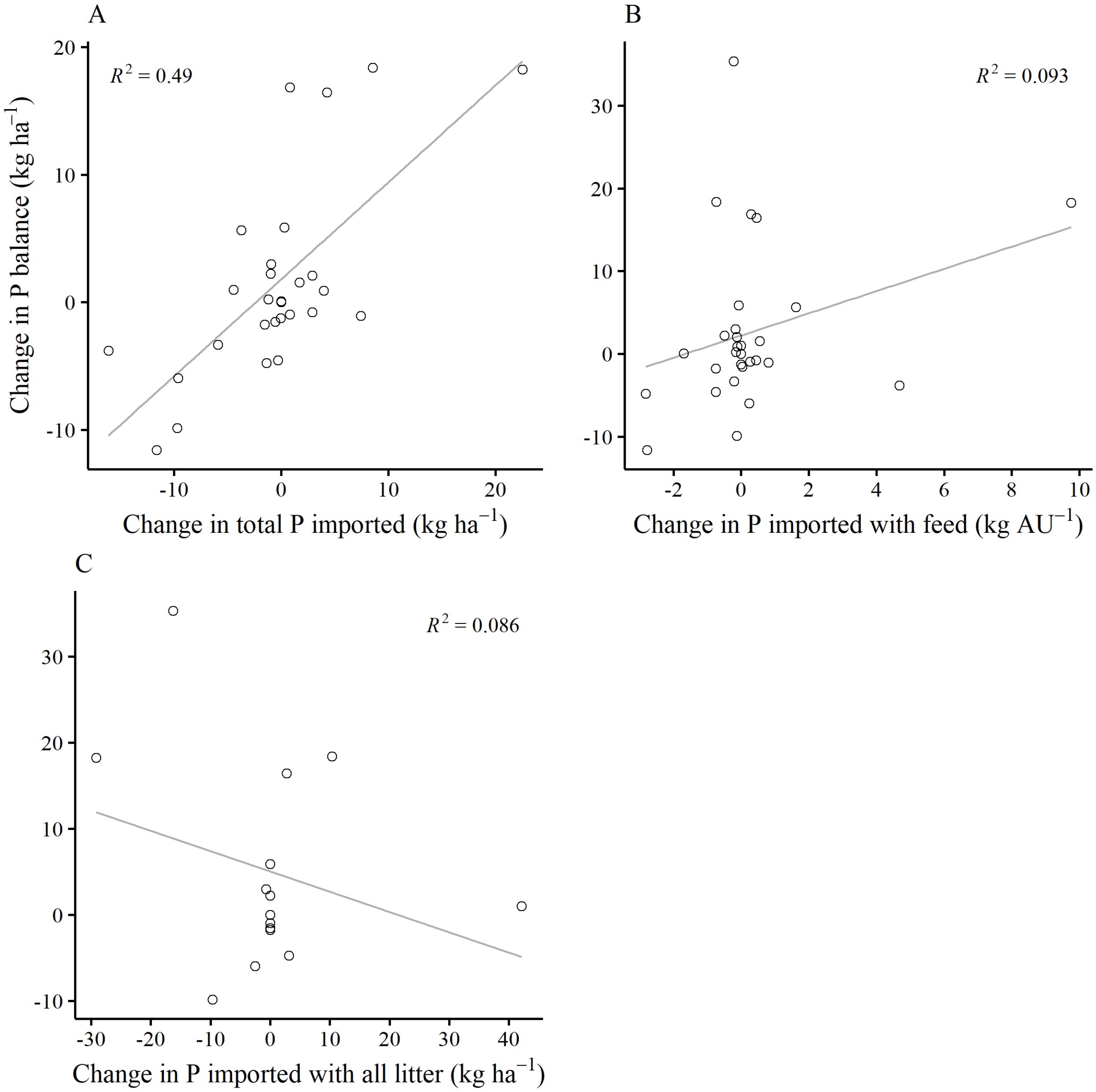

Figure 2-2. The change in P balance per hectare (kg ha^{-1}) is shown in relation to changes from 2017 to 2018 in total P imported (kg ha^{-1}), P imported with feed (kg AU^{-1}), and P from both generated and imported poultry litter. Plot A excludes two highly influential observations. The correlations in plots B and C were not significant ($p > 0.05$).

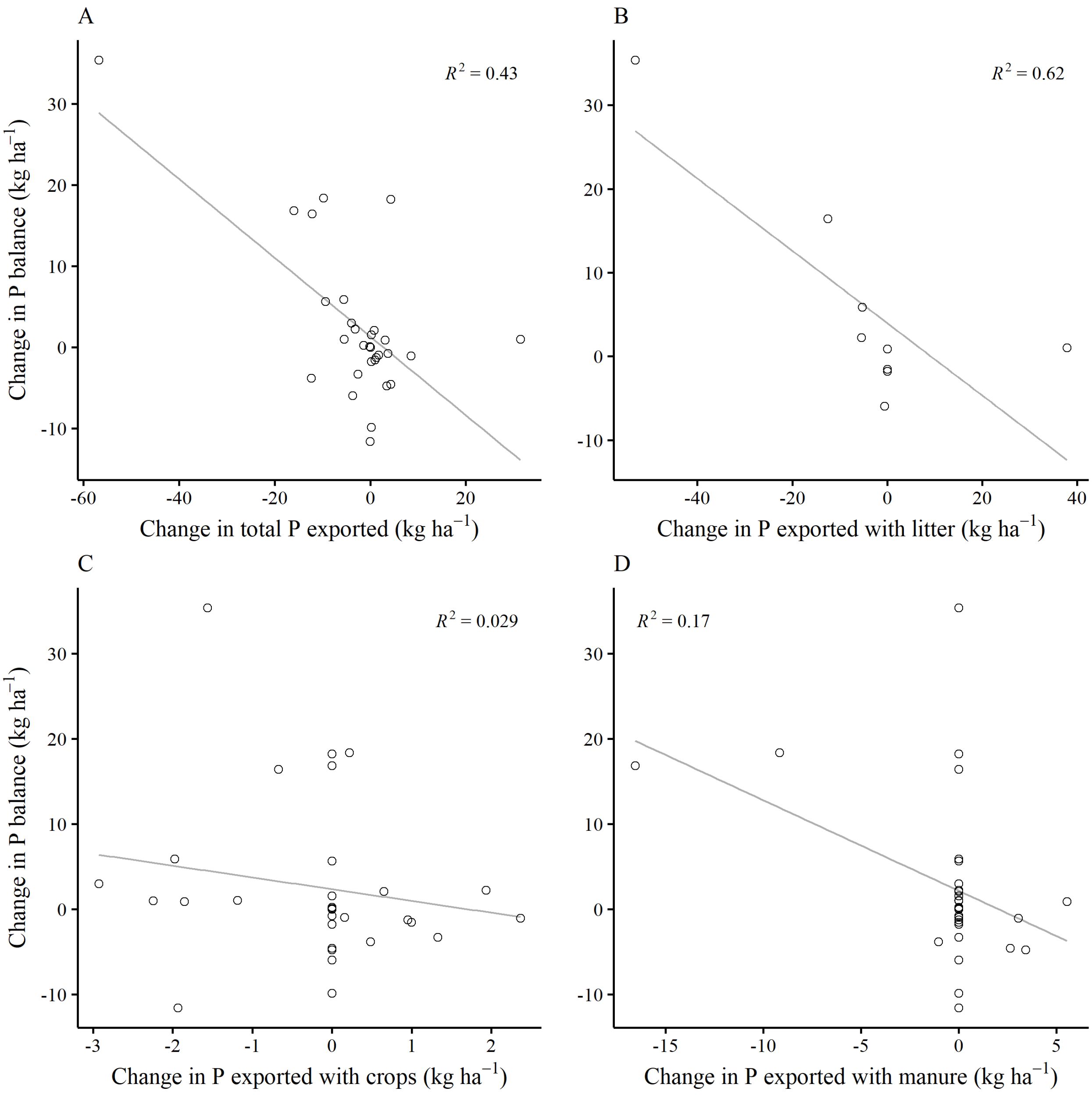

Figure 2-3. The relationship between changes in P balance per hectare (kg ha^{-1}) from 2017 to 2018 and changes in total P exported (kg ha^{-1}), P exported with generated litter (kg AU^{-1}), P exported with crops (kg ha^{-1}), and P exported with manure (kg ha^{-1}). Plot B shows only those farms that generated litter and were thus able to export.

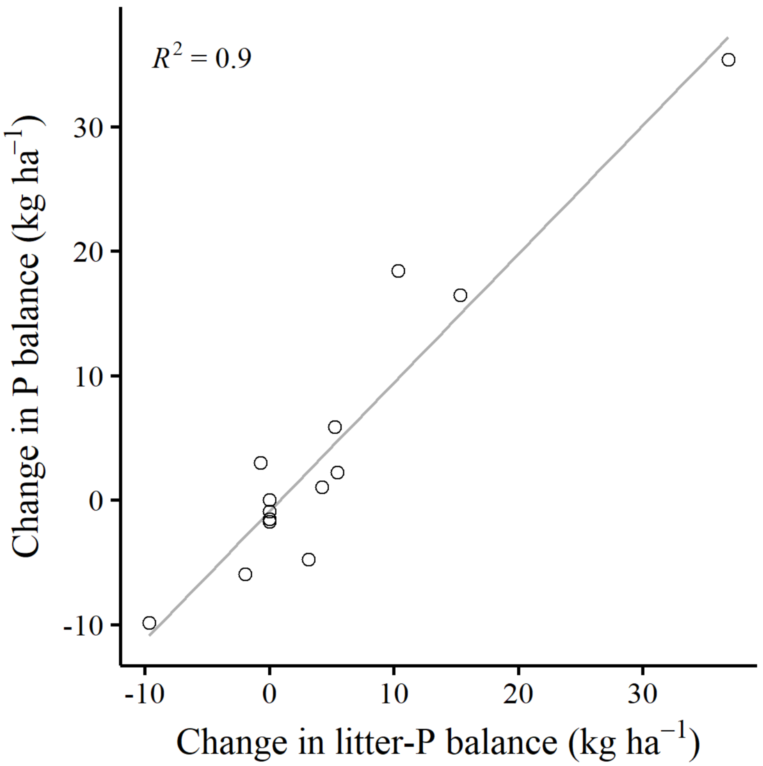

Figure 2-4. The relationship between changes in litter-P balance (a P balance subset associated only with imported and exported poultry litter) and changes in farm-gate P balance (kg-P ha^{-1}). Only farms that used poultry litter are shown.

Chapter 3: Phosphorus mass balance can be improved while maintaining or improving farm profitability: case study of a small Virginia dairy farm

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Abstract

Phosphorus (P) accumulation in dairy farm soils can be managed through P mass balancing at the farm scale. This study evaluated whether or not a small Virginia dairy farm can reduce its P surplus and improve its P use efficiency while maintaining or improving farm profitability. Working with a relatively typical, small dairy farm of 105 cows, financial and P balance records were obtained to build partial budgets in order to monitor change in farm net return due to changes in farming strategies. Factors adjusted included crop productivity and operating costs, with a range of outcomes under more and less favorable farming scenarios. After expanding the land base from 100 to 150 acres, the change in potential net return ranged from $-0.90 to $1.26/cwt of milk, with accompanying changes in P balance ranging from -9.0 to -14.7 lbs/ac. The analysis also showed that changes in potential net returns after converting to a grazing-based system ranged from $-2.14 to $1.39/cwt, with greater potential change in P balance ranging from -9.7 to -17.8 lbs/ac. The most profitable strategy generally for this farm seemed to be expanding the land base and growing a cash crop. Reducing P balance will ensure the farm halts further accumulation of soil test P, while not having significant impacts on farm profitability under expected farming conditions.

Introduction

Phosphorus Problem in Dairy Farming

Operating a dairy farm efficiently requires nutrient mass balancing, where farm scale outputs match inputs. One of those nutrients is phosphorus (P), vital to plant and animal biology and therefore, agricultural production. Comparing the total amounts of P imported and exported annually on a dairy farm is central to diagnosing the farm's status of nutrient management and efficiency. The flow of P through the farm gate is managed by the dairy farmer (Fig 3-1). When total P imports exceed total P exports, the positive P balance or surplus P is added to the internal cycling of P on the farm, and ultimately accumulates in the soil through manure applications (Wang et al., 1999). Beyond the farm scale, the spatial consolidation and concentration of animal farms had led to regional accumulations of P in soils (Maguire et al., 2007; Bouwman et al., 2013; Reid et al., 2019). When P accumulates to very high levels in agricultural soils, the risk increases for environmental losses. These losses not only degrade surface water quality, but are an unnecessary agronomic inefficiency.

Soil tests for the counties in Virginia with high densities of dairy farms and other animal agriculture show that at least 33% of farms test very high for STP (Maguire 2014, personal communication). If STP in the crop soils on a Virginia dairy farm is above the recommended 55 ppm Mehlich 1, then continued P surplus becomes a liability and environmental hazard as a source for phosphate pollution to surface waters. Having a P balance near 0 lbs/ac in these situations is ideal, representing the halt of STP accumulation. For farms with STP above the agronomic threshold, operating with a negative P balance (P exports > P imports) may even be tolerable as STP is mined through crop removal, though this takes time. One study found that for soils typical of dairy farms in Virginia, a P surplus of 8 lbs/ac (~18 lbs P_2O_5) tends to raise the

Mehlich 1 P concentration by 1 ppm per year (Maguire et al., 2008). Drawing down STP from elevated levels can take years of negative P balance and soil mining to reach optimal levels (McCollum, 1991; McDowell et al., 2020).

Options for Management

Many options are available to the producer for adjusting and managing the farm P balance sustainably, and this flexibility is key in adaptive farm management (Ketterings, 2014). Effective methods generally center around avoiding P fertilizer, improving feeding strategies, exporting crops and manure, and reducing animal density, usually by ensuring adequate land base.

Importing P fertilizers should be avoided on most dairy farms. Using fertilizers that specifically meet the nitrogen, potassium, and other nutrient needs will help limit excessively high P surpluses. On the export side, getting cow manure off-farm is a sure way to decrease P surplus and improve P use efficiency (PUE), especially on farms with higher animal densities (> 1.0 animal unit per acre) (Cela et al., 2014). Exporting manure is, however, limited by many factors including timing, availability, storage, and transportation. Hauling a liquid slurry is costly due to the weight of this high water content product. Finding ways to minimize the costs associated with transport has been the focus of other studies (Paudel et al., 2009; Sharara et al., 2017), and will not be involved in this study.

Improved feeding strategies can lower the amount of P imported annually with feed, by decreasing P concentrations or total amounts of feed purchased. Any P in purchased feeds, especially concentrate mixes of high energy and high protein grains, if fed above animal requirements will end up in manure to be soil applied (Anderson and Magdoff, 2000). In this context, a portion of the imported feed should be viewed as fertilizer. A study in New York assigned herds to a precision feeding program that reduced P intake by about 25% on average, reducing the farm P balances by 49% (Cerosaletti et al., 2004). Importantly, diets lower in P can still meet animal requirements (Knowlton and Herbein, 2002; Dou et al., 2002). Reducing mineral P intake down to the minimum recommended level improved farm profitability by about \$22/cow (Rotz et al., 2002). Ration reformulation and modified cropping goals improved another farm's profitability by about \$40,000 yr^{-1} (Klausner et al., 1998).

Improved feeding strategies also depend on appropriate homegrown feed production. Not only does adequate feed production potentially reduce the amount of feed purchased, but yields in excess of herd needs can be sold and exported (Cela et al., 2015b). Crop exports are an opportunity not only for revenue but to export P off-farm, and is particularly important on dairy farms with lower animal density (Cela et al., 2014). It also bears mentioning that fertilizer and manure should be applied to farm crops at P based rates to avoid soil test P accumulation and forced drawdown periods (Sadeghpour et al., 2017).

In a study of P balance on a sample of 58 dairy farms and mixed operation dairy farms in Virginia, Pearce and Maguire (2020) found a wide range of P balance among dairy farms. For 75% of the farms in that study, operating with an annual P balance below 16.7 lbs/ac was feasible, and 50% of farms achieved a PUE of 1.0 lbs-P/1000 lbs-milk or better. Though the use poultry litter was a clear risk factor for high P balance and worse PUE, some dairy farms instead appeared to struggle with limited land and homegrown feed production potential. For these smaller Virginia dairy farms, it is unclear how much P balance would really be improved or how much farm profitability would really be impacted under certain management scenarios known to reduce P balance.

This paper seeks to evaluate if a small Virginia dairy farm can lower its P surplus and improve its P use efficiency while maintaining or improving farm profitability. We will use a case farm to explore management options around land expansion and establishing a grazing-based system to achieve some combination of decreasing P mass balance while maintaining or increasing farm profitability. Such an evaluation will hopefully illustrate how farmers may choose to implement adaptive management strategies in harmony with business goals and environmental regulations and stewardship.

Materials and Methods

Multiple dairy farms were approached about participating in this financial study, after having participated in previous P balance studies in 2017 and 2018. One of these farms represented a typical, small Virginia dairy farm, and they volunteered to provide further records on farm management and finances. In addition, this farm like others was struggling to make a profit, with a net return of $-0.32/cwt of milk.

Case Farm Description

The case farm is a conventional, small dairy farm somewhat typical for the Shenandoah Valley region of Virginia. Table 1 shows a comparison of the case farm, including its P balance components, with the average small Virginia farm from 2017. Around this time, the small farm began looking to expand from 100 to 150 ac through land acquisition. The herd composition used throughout this study consisted of 105 Holstein cows (lactating and dry) weighing around

1,400 lbs mature, 30 heifers over a year in age, 25 heifers between 4-12 months old, and 25 calves. In 2018, they reported producing approximately 22,420 lbs milk per cow, for $17.27 per hundredweight (cwt) of milk. Thirty-eight cows were culled, and bull calves were sold immediately. Imported feed included grain and protein mixes, mineral-added heifer premix, whole cottonseed, wet brewers grain, hay, and calf milk replacer. Grazing cows was not a significant feeding strategy, with only about 15 ac of pasture available for hay production.

Homegrown crops included corn for silage, corn for grain, winter rye for silage, and grasses for hay. Corn was in rotation with soybean, and the farmer has reported selling a portion of corn grain and soybeans off farm. Overall soil productivity for the farm was low (VA DCR, 2014). The farmer reported no imports of P fertilizer or poultry litter for land application, and about 75-100 ac of crop land received regular broadcast applications of manure. When the farm was 100 ac, about 60,000 gal of liquid slurry dairy manure was exported from the farm. It should be noted that the case farm is in an area with other nearby dairy farms, and opportunities to export manure are often limited. Kiln-dried pine sawdust was imported as a bedding material, though it had a very low P concentration of about 0.32 lbs P per ton of sawdust.

Data Required

The farm management, P balance, and financial data required included information on farm production, farm imports and exports, operating costs per production unit, and feed and animal prices. Some of the farm characteristics and management data was collected during the 2017 and 2018 P balance farm visits, and included acreage, animal numbers, crop yields, and milk sold. The methodologies for collecting and calculating P balance data have been described in detail (Pearce and Maguire, 2020). In short, P mass balancing required information on the total amounts and P concentrations of P-containing imports and exports brought onto or taken off the farm during a calendar year, and may include: purchased feed mixes and supplements, commercial chemical fertilizers, imported animal fertilizers such as poultry litter, bedding materials, animals sold, milk sold, crops sold, and cow manure exported. The difference between the total mass of P imported and exported annually is the P balance (Fig 3-1), which may be reported on a per acre basis or per production unit basis. Other forms of P loss from the farm may include surface runoff or erosion, but this was not included in the managed P exports for the focus of this study. The small amount of P lost to the environment has been included in nutrient mass balance assessment in other studies (Rotz et al., 2020).

Financial data was voluntarily shared by the farmer. The income statement, a Schedule F income tax form, listed farm revenues and expenses in somewhat limited detail. The Schedule F validated another record the case farm also shared voluntarily without request: a summary report from its previous participation in a financial benchmarking program known as the Farm Credit of the Virginias' Dairy Management Institute. From these, information was extracted including total revenues and total expenses, prices for milk and feed, veterinary and milk hauling expenses, and so on.

Other financial data collected included cropland rental rates (used to estimate the cost of increasing cropland) and operating costs of production. These data were obtained through sources like the National Agricultural Statistics Service (NASS) and the Virginia Cooperative Extension enterprise budgets that can be found in the Ag Risk + Farm Management Library maintained by the University of Minnesota (UMN, 2020).

Partial Budget Analysis

To determine the change in net return to the farmer under different management strategies, we first developed partial budgets, having been demonstrated in previous studies of dairy farms (Klausner et al., 1998). The Excel-based partial budgets focused only on changing the factors of interest, holding other factors constant in order to isolate the effect of a change of grouping of changes. Factors changed included total acres, acres assigned to certain crops, crop yields, milk yields, and variable operating costs. Any new acres added to the farm's land base were assumed to have similar soil productivity as the original acres.

Feed and milk prices were kept constant so as to isolate the management changes from market volatility. Besides, a study in Wisconsin that performed some sensitivity analyses found that changes in feed or fertilizer prices had little effect on net returns compared to other changes (Pellerin et al., 2017). Operating costs were extracted from enterprise budgets, and included such costs as seed, non-P fertilizers, hauling, repairs, labor, etc. These partial budgets focused on operating or variable costs, and as such did not endeavor to capture finances related to loans or depreciation.

Rather than produce a single, neutral outcome for a management strategy, a range of scenarios were created by modifying the neutral scenario for unfavorable and favorable operating conditions. These are referred to respectively as simply "worse" and "better" in the results. Modifying scenario favorability involved adjusting factors like costs of crop production, crop yields, or milk production in the various management scenarios in order to learn how sensitive farm profitability was to changes that would improve P balance. In essence, a worse outcome reflected poorer operating efficiency and below average crop yields, while a better outcome represents increased operating efficiency and above average crop yields.

Management Strategies and Scenarios

A few criteria guided the selection of strategies to be explored. First, P balance must be decreased. Second, herd size would be maintained to isolate the analysis from changes in efficiency that might come with scaling up to a larger operation. Lastly, strategies must involve some degree of increased land as the farmer had mentioned an opportunity they had to make such a change.

The chosen farm management strategies and scenarios explored are summarized in Table 3-2. Three strategies were explored: 1) expand the land base and scale up the homegrown feed production; 2) expand the land base and scale up cash crop production; and 3) expand the land base and establish a grazing-based system. For each of these strategies, various scenarios were tested and outcomes were compared.

Strategy 1: expand the land base and scale up the homegrown feed production

The first management strategy expanded the farm's land base while maintaining a conventional operation. This strategy involved renting an additional 50 acres of adjacent crop land, as the farmer had considered doing. These acres were used to scale up the production of homegrown hay, aiming for self-sufficiency in growing all needed forage. In this way, the final dairy ration did not change and milk yield was thus unaffected.

Factors in expanding that could potentially increase costs were: additional land costs, changes in feed purchases, and costs of increased crop production. As the same variety of crops were to be grown, no additional equipment was needed for planting or harvesting. Manure hauling costs were added as the previously exported manure was land applied. Reducing purchased forage from off-farm would decrease costs. The following scenarios are also summarized in Table 3-2.

Scenario 1N: scale up under neutral conditions

The neutral scenario (1N) for expanding from 100 to 150 acres kept factors at typical values the farm has experienced, like operating costs, milk yield, and crop yields. Crop yields were: 17 t/ac for corn silage, 140 bu/ac corn grain, 10 t/ac for rye silage, and 2.25 t/ac for hay, as reported by the farmer. The additional 50 acres was assigned entirely to hay, and hay was only purchased off-farm if homegrown yields were inadequate. Total acres allotted for other crops were not altered.

Scenarios 1W and 1B: scale up under worse and better conditions

A "worse" outcome scenario (1W) that represented unfavorable operating conditions was created from 1N. Crop yields were diminished: corn silage to 15 ton/ac, corn grain to 125 bu/ac, 9 ton/ac for rye silage, and 1.8 ton/ac for hay. Crop production costs increased 10%. As corn silage yields were lower, winter rye acreage was increased as needed. A drop in milk yield could result from substitutions between rye silage and hay and corn silage.

A "better" outcome scenario (1B) was also designed, reflecting more favorable farming conditions than 1N. Crop yields increased: corn silage was harvested at 19 ton/ac, corn grain at 155 bu/ac, rye at 11 ton/ac, and hay at 2.7 ton/ac. Crop production costs were dropped 10%. Excess forage grown beyond herd requirements were sold off.

Strategy 2: expand the land base and add cash crop production

The second strategy was similar to the first, in that land base was expanded for additional crop production. Whereas the first strategy aimed to be self-sufficient at homegrown feed production, the second strategy used the additional land for growing a cash crop of corn for grain. The 50 acres rented were used to generate revenue, with other feed requirements being met through off-farm purchases or increased production on the original 100 acres. The goal again was not to change the dairy ration, thus maintaining milk yield. Strategy 2 scenarios are summarized in Table 3-2.

Scenario 2N: expand and add cash crop production under neutral conditions

The neutral scenario for strategy 2 (2N) was set up like scenario 1N in terms of crop acreage, yields, and operating costs. The additional 50 acres were used for corn grain production, grown to an expected yield of 140 bu/ac.

Scenarios 2W and 2B: expand and add cash crop production under neutral conditions

Similar to scenario 1W, the worse outcome for strategy 2 (scenario 2W) involved a decrease in crop yields to the previously mentioned amounts. With a slight change in dairy ration, milk yield was reduced by 2% as in scenario 1W. Operating costs increased 10%, and rye silage acres were increased from 32 to 51 ac to help cover the diminished yields of corn silage and hay, while additional hay was imported as needed. The better outcome for strategy 2 (scenario 2B) followed the same crop yield increases and operating cost decreases as scenario 1B (Table 3-2).

Strategy 3: convert to grazing-based system

This third strategy explored the effects of converting to a grazing-based dairy farm system. The goal was to first expand the 100-acre farm by renting an additional 50 acres, then converting it to orchardgrass (*Dactylis glomerata*) pasture, producing anywhere from about 3,000 to 5,000 lbs DM/ac (University of Wisconsin-Extension, 2002). In order to meet dry matter intake and forage requirements of the 105-cow herd, another 50 acres of cropland was rented to continue corn silage and rye silage production, bringing total acres to 200.

Factors that could potentially increase revenue were increased sales of choice heifers due to reduced culling rates and selling excess forage. Reduced revenues would occur with decreased milk yield and fewer cows sold as culls. A switch to more intensive, rotational grazing would result in a reduced milk yield per cow of at least 5% due simply to increased exercise and lower energy and higher fiber of grass over corn silage (Broderick et al., 2002). For high performing cows on a total mixed ration, milk yield could be reduced by as much as 30% (Kolver and Muller, 1998). The cows on the case farm were not, however, high performing (22,630 lbs/cow annually), and their grazing was still supplemented throughout the year with necessary high energy and protein feeds, albeit in diminished amounts. Culling rates were reduced 15%, and veterinary expenses were reduced 30% as grazed cows can experience improved health over confinement (Rotz et al., 2002).

With less milk produced, milk hauling and marketing costs would reduce expenses, along with less manure hauling expense. Cost associated with harvesting hay was also a reduced expense. Purchased feed expenses would also decrease, along with the stop of corn grain production on farm. Imported pre-mix feeds for heifers were maintained as possible. Increased expenses were expected from additional land costs, fencing and watering installation, and establishment and maintenance of the pasture.

Scenario 3N: Grazing-based system under neutral conditions

For the neutral grazing scenario (3N), 150 acres were established with orchardgrass and red clover, with an expected yield of 4,000 lbs DM/ac. Corn and rye silage yields were typical of the farmer's record, at 17 and 10 ton/ac, respectively. With an increased reliance on forage in the diet, feed grain purchases were reduced and milk yield was reduced by 15%. No acres were available for growing corn grain.

Scenarios 3W and 3B: Grazing-based system under worse and better conditions

A worse outcome scenario (3W) that represented unfavorable crop yields and less efficient operating conditions was created by first reducing pasture yield from 4,000 to 3,000 lbs DM/ac. Corn silage and rye silage yields were diminished to 15 and 9 ton/ac, respectively. Milk yield was reduced by 20% to represent worse cow performance. With lower forage yields, winter rye acres were maximized from 32 to 50 acres in order to minimize imported forage. Operating costs were increased 10%.

The better outcome scenario (3B) assumed pasture production closer to the suggested 5,000 lbs DM/ac, with corn silage yield at 19 ton/ac and rye silage yield 11 ton/ac. Milk yield was only reduced by 10%, and operating costs were decreased 10% to reflect improved efficiency. Rye acres were not maximized, and excess forage produced was sold off the farm.

In all scenarios, the purchase of additional P fertilizer was avoided in order to minimize P balance. Soils in the region are often found to be much higher in STP than the recommended agronomic level of 55 ppm Mehlich 1 (Maguire, 2014, personal communication). Previous research has also shown that for soils in the region of this case farm, soil test P concentrations increased on average by 1 ppm for every 8 lb P/ac added through poultry litter applications (Maguire et al., 2008). When comparing scenarios for ideal outcomes, preference was to choose scenarios in which P balance was not only reduced, but in which it was reduced to near or below 8 lbs P/ac, effectively stabilizing STP. The tonnage of feeds was reported on a dry matter basis.

Results and Discussion

Base Strategy

From farm records, the base strategy was not profitable. Farm crop production was 458 ton of silages and 44 ton of grass-based forage in addition to 70 ton of shelled corn grain, retaining 20 ton for feed. Another 90 tons of hay for forage was imported, along with 246 tons of grain concentrates, and 72 tons of wet brewer's grains (Table 3). The yields reported by the farmer were reflective of low productivity soils in the area (VA DCR, 2014).

The annual P balance was 19.0 lbs/ac and P use efficiency (PUE) was 0.81 lbs-P/1000 lbs-milk. The P balance exceeded the suggested threshold of 16.7 lbs P/ac, but PUE was better than the median 1.0 lbs-P/1000 lbs-milk previously observed (Pearce and Maguire, 2020). Virtually all P imported was associated with feed purchases, and milk sold was the main P export

(Table 1). The high P balance and net return of $-0.32/cwt of milk suggested room for improvement.

Strategy 1: expand the land base and scale up the homegrown feed production

Under the neutral scenario 1N, expanding from 100 to 150 acres and scaling up homegrown feed production increased the dairy farms ability to produce forage and decrease hay imports (Table 3). With the added acreage, the animal density decreased to 1.3 AU/ac. An additional 101 ton of grass hay were produced, resulting in a net sale of 11 ton of hay off the farm. With no imported forage and with additional land, P balance improved by decreasing by 9.4 lbs/ac. PUE was improved, too, measuring 0.61 lbs-P/1000 lbs-milk. The change in net return was $-0.16/cwt, showing the expansion to be less profitable as the cost of growing hay on additional land was greater than the cost of importing hay. Groover (2007) showed that, for a 100 ac farm with 40 cows, grazing and purchasing hay was a more profitable strategy overall than was producing one's own hay, as this required the added costs of hay making machinery, for example.

This outcome (1N) depended on maintaining previous yields, including for the newly acquired land. Under the worse favorability scenario (1W), yields were diminished, though acres of rye silage were increased to help compensate. Milk yield was reduced 2% as rye silage and hay made up a greater proportion of the ration with diminished corn silage yields. Homegrown silage production actually increased slightly with the added rye acres, and no additional hay was imported (Table 3). The change in P balance was -9.0 lbs/ac, due to decreased feed imports and added acres, and PUE improved slightly to 0.65 lbs-P/1000 lbs-milk due to decreased feed imports. Net return was affected by increased operating costs, reduced corn grain sales, as well as increases in operation due to extra rye and hay acres. The change in net return from the base scenario was $-0.90/cwt, suggesting that the farmer may be far worse off financially in a tough year than if they had remained operating on the smaller land base. In fact, 1W was the least profitable outcome for all tested scenarios.

The better favorability scenario (1B) was the only scenario in strategy 1 with a positive net return. Homegrown silages produced 510 ton, with 171 ton of grass hay produced, enough for 90 ton to be sold (Table 3). And extra 7 ton of corn grain were sold, further increasing revenues. The reduction in P surplus was greater, with a change in P balance of -11.8 lbs/ac due to increases in exported crops along with added land. PUE was improved to 0.46 lbs-P/1000 lbs. Change in net return was $0.36/cwt, or $80/cow, resulting in a positive net return of $0.04/cwt.

The net returns of scenarios 1N, 1W, and 1B lean negative, suggesting that self-sufficiency in homegrown feed production may not be economically feasible unless other factors are improved (e.g. milk yield, operating costs, etc.). Klausner et al. (1998) showed a significant improvement in farm net returns after increasing homegrown feed production, but this was due to ration reformulations that increased milk yield and decreased purchased feeds, whereas the costs associated with farm produced feeds actually decreased farm net income.

Strategy 2: expand the land base and add cash crop production

Scenario 2N was very similar to Scenario 1N, except that corn grain yields were increased significantly (exporting 217 ton) which improved farm revenue and increased P exports (Table 3-3). Hay continued to be imported (90 ton) to match herd ration requirements, increasing P imports relative to Scenario 1 which was self-sufficient on feed. The net change in P balance was greater than 1N at -12.5 lbs/ac, bringing the overall P balance to 6.5 lbs/ac, potentially low enough to sufficiently slow soil P accumulation. Improvements in PUE were also seen for scenario 2N, coming to 0.41 lbs-P/1000 lbs-milk. The net returns were favorable with an increase of $0.80/cwt due to greatly increased revenues from corn grain sales.

Worse farming conditions in 2W resulted in similar outcomes to 1W, though homegrown hay decreased 6 ton, requiring a slight increase in purchased hay. Operating costs were further increased as rye silage acres increased to 51 ac to compensate for corn silage losses. Corn grain yields were lower and resulted in 191 ton being sold, with reduced revenues relative to 2N. Change in P balance was -11.0 lbs/ac, and PUE still improved to 0.52 lbs-P/1000 lbs-milk. Even under worse farming conditions, the revenue from corn grain sales offset the increased operational costs, and change in net return was $-0.01/cwt.

Better outcomes in scenario 2B resulted in the most profitable scenario tested (Table 3). With 510 ton of silages produced, 53 ton were available for sale. Sold also were 242 ton of corn grain after an above average yield of 155 bu/ac was achieved, increasing both revenues and P exports. Purchased hay was reduced slightly to 85 ton which reduced P imports. Change in P balance was -14.7 lbs/ac, bringing the P balance closest to zero out of the Strategy 1 or 2 scenarios. PUE was also the most improved at 0.27 lbs-P/1000 lbs-milk. Net returns were increased by $1.26/cwt to a net gain of $0.94/cwt, a significant result for a farm that began with net losses. The scenario results for Strategy 2 were generally more profitable and had lower P balances than Strategy 1, suggesting that from a financial perspective this farm should consider using the additional land for profit-generating revenue rather than establishing feed self-sufficiency.

Strategy 3: grazing-based system

Converting to a grazing-based system resulted in the widest range of outcomes of the three strategies (Table 3-3). Operating on 200 ac, the animal density dropped to 1.0 AU/ac. Based on suggested formulas (University of Wisconsin-Extension, 2002), the 150 acres of pasture would likely be insufficient for a 100% grazing system. However, the 200 acres of pasture and silage were found to produce ample forage as the cows and older heifers were still supplemented with grains and protein feeds, basically using a partial total mixed ration feeding approach. This approach has been shown to be less profitable in daily net income than a total mixed ration approach, but more profitable than a pasture-based diet (Tozer et al., 2003).

Under a neutral scenario (3N), 380 ton of silages and 300 ton of dry matter were produced from grass pasture, allowing hay imported to stop. No corn grain was produced, resulting in lower revenues and decreased P exports. The shift to a higher forage diet (75% forage) meant that grains and protein feeds imported were reduced by 22%. This reduced expenses significantly, decreased P imports, and improved net return. Milk yield was dropped in the grazing-based system by 15%, greatly reducing revenues and reducing P exports. The additional acres and the reduced feed imports resulted in a net negative change in P balance at -12.5 lbs/ac, while PUE was also improved to 0.65 lbs-P/1000 lbs-milk. The change in net return for 3N was unfavorable at $-0.38/cwt.

For scenario 3W, a worse outcome included pasture yields of just 3,000 lbs/ac, representing poorly managed grazing and pasture. Total silage yield was similar to 3N at 387 ton as rye silage acres were maximized to compensate for loss in corn silage yields, though this was accompanied by increased operating costs. Feed imports increased relative to 3N as additional hay (69 ton) was imported as needed. The worse outcome decreased revenue as milk yield dropped another 5% points to 17,936 lbs/cow.

With imported feed and decreased milk, the change in P balance was -9.7 lbs/ac, less than in the neutral scenario. PUE increased to 0.99 lbs-P/1000 lbs-milk, slightly above the base PUE and the only time PUE increased in the scenarios tested. PUE was equal to the median of all Virginia dairy farms studied in 2017 (Pearce and Maguire, 2020). In a grazing-based system with poor forage yields and worse milk yields, profitability was reduced significantly by $-2.14/cwt.

The better outcome scenario (3B) for a grazing-based system represented the most ideal outcome for this small farm, with better net returns, less loss in milk yield, and lower P balance. While milk yields were expected to decrease, the farm managed 20,178 lbs/cow, and so revenue reductions were not as great as 3N or 3W. With 5,000 lbs/ac of pasture dry matter achieved along with increased corn and rye silage yields, 152 ton of excess forage were ultimately exported from the farm, decreasing P balance and increasing revenues. The change in P balance was -17.8 lbs/ac, the greatest drop across all scenarios, bringing the P balance near zero at 1.2 lbs/ac. In scenario 1B, PUE was likewise the lowest than other scenarios at 0.11 lbs-P/1000 lbs-milk, suggesting that a well-managed grazing system was the most efficient option tested from a P mass balance perspective. This scenario also resulted in the best net return at $1.07/cwt, an increase of $1.39/cwt. Scenario 3B also suggests that a grazing-based system will not be profitable unless the farmer can ensure well managed pastures and that cow performance can reach higher yield goals.

Across all grazing scenarios, improvements in P balance tended to be greater than in Scenario 1, though similar to Scenario 2 in which cash crop exports vitally increased P exports. This reflected the lower environmental impact of grazing-based dairy farms, which in part have lower P imports and in part have more land upon which to diffuse any P surplus. Rotz et al. (2002) reported a substantial 52% decrease in P balance after a 100-cow dairy in New York transitioned to intensive grazing. Flemish grazing dairies had slightly better P surplus (3.2 lbs/ac less) than their confinement-based counterparts with equivalent return on assets (Meul et al., 2012).

The 3N and 3B scenarios showed a net return increase ranging from $-62.6 to $288/cow (Table 3-3). In Pennsylvania, a 200-acre and 53-cow dairy farm adequately met its needs under a pasture-based grazing system, with net returns $121/cow higher than the confinement option (Parker et al., 1992). Though the case farm may require time to adapt to a grazing-based strategy and to do it well, moderate intensive grazing has been shown to be profitable while, importantly, grazing experience of the farmer was not highly significant (Hanson et al., 1998). A grazing-based system may also provide some benefits of market resiliency, as a conventional total mixed ration system can be sensitive to higher feed prices and lower milk prices (Tozer et al., 2003).

Overall Strategy Assessment

To support decision making from candidate strategies, we present two plots which style has not been presented in previous research (Figs. 3-2, 3-3). We think such plots could expedite the educational process in which farmers are shown options that improve nutrient balance and use while improving or not affecting farm net returns. In looking at those outcomes that improved P balance and either increased net return or had no significant effect of net return (Fig. 3-2), the main candidate appeared to be strategy 2 (growing a cash crop). Self-sufficient homegrown feed production was only a candidate strategy if the farmer could guarantee sufficient yields (1B). Given the wide variability in milk yield per cow than can occur in a grazing-based system, strategy 3 seems like a candidate only when ample pasture production and minimal losses to milk yield can be ensured. With the additional land as the main contributing factor, all strategies were capable for decreasing P balance below the 75% threshold suggested by Pearce and Maguire (2020). In terms of PUE (Fig. 3-3), all strategies were at acceptable levels, showing better efficiency than the median dairy farm (Pearce and Maguire, 2020).

Other considerations

The better outcome scenarios all assumed the farmer improved the crop of corn silage, with yields increasing from 17 to at least 19 ton/ac. The likelihood of this outcome seemed restricted by the limited productivity of the farm's soils, though some soils in the region expect corn silage yields between 19-22 ton/ac (VA DCR, 2014). For the analysis, new acres were assumed to have the same soil productivity as the original acres. If, however, new acres were actually more productive, then obtaining more acres may in fact be a motivating factor for this farm to expand its land base. Permanently raising the average yield of homegrown forages through the acquisition of more productive fields may make a better scenario outcome more likely. Also, considerations could be made in regards to crop rotations, as double cropping rye with corn silage can limit corn silage yields despite improving environmental impacts from those acres (Krueger et al., 2012).

As shown with the grazing-based scenarios, farm net return was highly sensitive to milk yield. While variability in milk yield losses due to grazing can be diminished (Delagarde and Peyraud, 2013), Further analysis should be conducted to determine the sensitivity and relationship between milk yield, net return, and P balance. Another consideration for farm management relates to scaling the whole operation. While land may be limiting, managing a smaller herd of about 100 cows may also be challenging their capability to operate in an economically efficient manner, though still possible (Groover, 2001).

The scope of this research did not account for changes in P balance or net returns over a multiple year period, nor did it account for changes in other nutrients of environmental interest, such as nitrogen. A more complex analysis would be needed to account for different crop rotations, double-cropping options, projections in market prices, or averaging of weather patterns. This has been the focus of other tools and research. The N-CyCLES (**N**utrient **C**ycling: **C**rops, **L**ivestock, **E**nvironment and **S**oil) linear optimization Excel add-in (Wattiaux, 2016; Pellerin et al., 2017), and the Integrated Farm System Model (IFSM) software both seem like potential candidates for exploring further the connection between P balance and farm net returns. Provided by the Agricultural Research Service of the United States Department of Agriculture (USDA-ARS, 2020), IFSM has been recently shown to provide a more complete output of environmental impacts of complex and integrated systems such as dairy farming (Rotz et al., 2020).

Conclusion

For the case small dairy farm, expanding the land base seems to be critical to achieving both goals of profitability and environmental stewardship. Establishing an exceptionally-managed grazing-based operation seemed to be the most profitable option, while generally expanding to grow a cash crop for revenue was not only profitable on average, but reduced P balance significantly.

In addition, the partial budget approach proved a simple and effective decision support tool for farm managers considering changes and estimating the impact those changes may have on net returns, though the tool relies on the thoroughness of the user. Limitations may exist, however, in land availability for many small dairy farmers, and whether they would make such a significant transition should be studied further.

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Tables and Figures

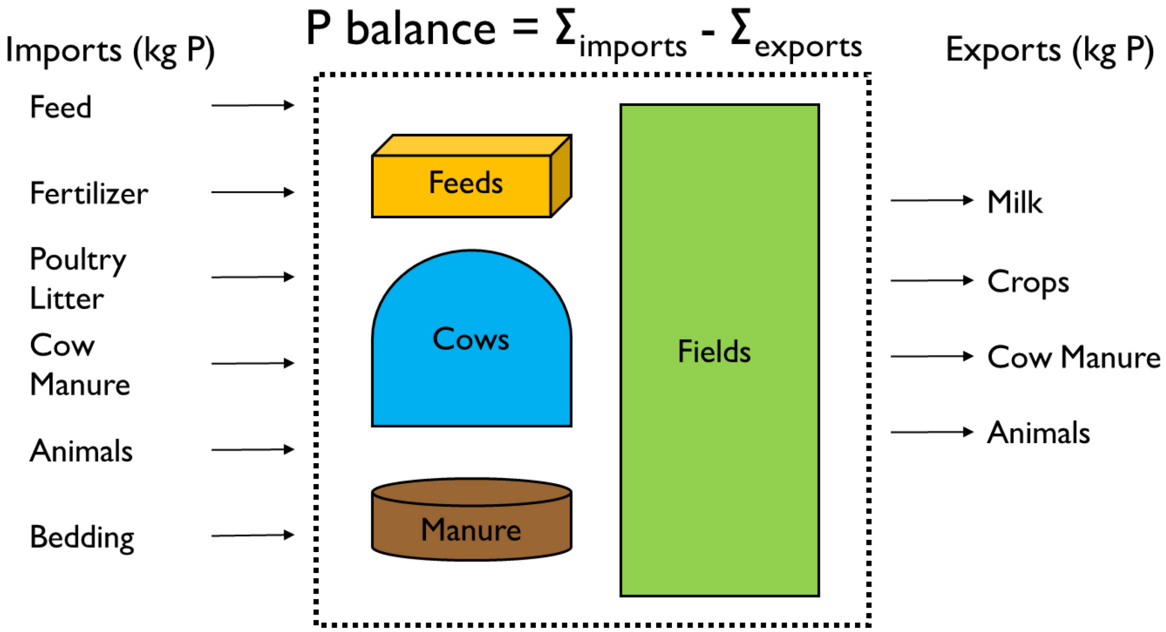

Figure 3-1. The difference between the total mass of P imported and exported annually is the P balance. Components of the farm-gate P balance are manageable and within the farmer's control.

Table 3-1. Summary of mean farm characteristics and P balance for 37 small (<200 cows) Virginia dairy farms in 2017, in comparison to the case farm.

Characteristic	Unit	Avg. Farm	Case Farm
Total acres (incl. rented)	ac	218	100
Mature dairy cows		104	105
Animal Density	AU/ac	1.3	1.9
Milk per cow	lbs/cow/yr	23,620	22,420
Milk per area	1000 lbs/ac	13.5	23.5
Percent land manured (%)	%	74	75
P Balance	lbs/ac	9.0	19.0
P Use Efficiency	lbs-P/milk*	1.27	0.81
Imported P	lbs/ac	29.5	52.8
Feed		24.0	52.2
Fertilizer		0.3	0.0
Other		5.2	0.6
Exported P	lbs/ac	20.5	33.8
Milk		13.5	23.5
Animals		2.2	4.0
Crops		1.9	3.9
Manure		2.9	2.4

Table 3-2. Summary of management strategies and their respective scenarios analyzed using partial budgets. Changes described in the worse and better scenarios include changes made in neutral scenario unless otherwise adjusted.

	Neutral (N) Scenario	Worse (W) Scenario	Better (B) Scenario
Base	Maintain current operations		
Strategy 1	• Rent additional 50 acres • Scale up feed production (hay) • Increase manure hauling • Average crop yields • 0% change in milk yield	• + 10% VC • Crop yields reduced ~10% • Increase small grain acres if needed • Buy forage if deficit • -2% milk yield	• - 10% VC • Crop yields increased ~10% • Sell excess forage • 0% change in milk yield
Strategy 2	• Rent additional 50 acres • Add cash crop production • Increase manure hauling • Average crop yields • 0% change in milk yield	• + 10% VC • Crop yields reduced ~10% • Increase small grain acres if needed • Buy forage if deficit • -2% milk yield	• - 10% VC • Crop yields increased ~10% • Sell excess forage • 0% change in milk yield
Strategy 3	• Rent additional 100 acres • Establish grazing-based system • Reduce manure hauling • Average crop yields • -15% milk yield • Vet costs -30% • Cull cows -15% (increase heifer sales)	• + 10% VC • Crop yields reduced ~10% • Increase small grain acres if needed • Buy forage if deficit • -20% milk yield	• - 10% VC • Crop yields increased ~10% • Sell excess forage • -10% change in milk yield

VC = Variable Costs (Operating costs associated with crop production)

Table 3-3 A comparison of annual production and economic outputs for various farm management scenarios on a 105-cow dairy farm in Virginia. Scenario 1 (expand existing operation to 150 ac) is shown under neutral (N), worse (W), and better (B) favorability conditions, with net return based on partial budgets. Scenario 1 was also modeled using IFSM software, under neutral conditions (1N) and under an alternative (1A) scenario with higher forage use in rations.

			Self-sufficient			Cash crop for revenue			Grazing-based system		
Output	Units	Base	1N	1W	1B	2N	2W	2B	3N	3W	3B
Land base	ac	100	150	150	150	150	150	150	200	200	200
Animal density	AU/ac	1.9	1.3	1.3	1.3	1.3	1.3	1.3	1.0	1.0	1.0
Milk production	lbs/cow	22,420	22,420	21,972	22,420	22,420	21,972	22,420	19,057	17,936	20,178
Homegrown crops	ton DM										
Silages		458	458	473	510	458	459	510	380	387	456
Grains		20	20	20	20	20	20	20	0	0	0
Grains Sold		50	50	40	57	217	191	242	0	0	0
Grasses		44	145	119	171	44	38	50	300	225	375
Forage Sold		0	11	0	90	0	0	53	0	0	152
Imported items	ton DM										
Forage		90	0	0	0	90	96	85	0	69	0
Grains/Concentrate		246	246	246	246	246	246	246	195	195	195
Wet Brewers Grain		75	75	75	75	75	75	75	59	59	60
P Imported	lbs/ac	52.8	30.6	30.6	30.6	35.2	35.6	30.6	18.2	20.4	18.2
P Exported	lbs/ac	33.8	21.0	21.0	23.4	28.7	27.6	23.7	11.7	11.1	17.0
P Balance	lbs/ac	19.0	9.6	10.0	7.2	6.5	8.0	4.3	6.5	9.3	1.2
P Use Efficiency	lbs/milk*	0.81	0.61	0.65	0.46	0.41	0.52	0.27	0.65	0.99	0.11
Change in P Balance	lbs/ac	-	-9.4	-9.0	-11.8	-12.5	-11.0	-14.7	-12.5	-9.7	-17.8
Change in P Balance	lbs/milk	-	-0.20	-0.16	-0.35	-0.40	-0.29	-0.54	-0.16	0.18	-0.70
Total Cash Income	$/cwt	18.9	19.0	18.9	19.4	19.9	19.8	20.3	19.4	19.5	20.1
Total Cash Expense	$/cwt	19.2	19.5	20.1	19.4	19.5	20.2	19.3	20.1	22.0	19.0
Net Return	$/cwt	-0.32	-0.48	-1.22	0.04	0.48	-0.33	0.94	-0.70	-2.46	1.07
Change in Net Return	$/cwt	-	-0.16	-0.90	0.36	0.80	-0.01	1.26	-0.38	-2.14	1.39
Change in Net Return	$/cow	-	-35.7	-196	80.2	178	-1.10	282	-62.6	-369	288

*per 1000 lbs of milk sold.

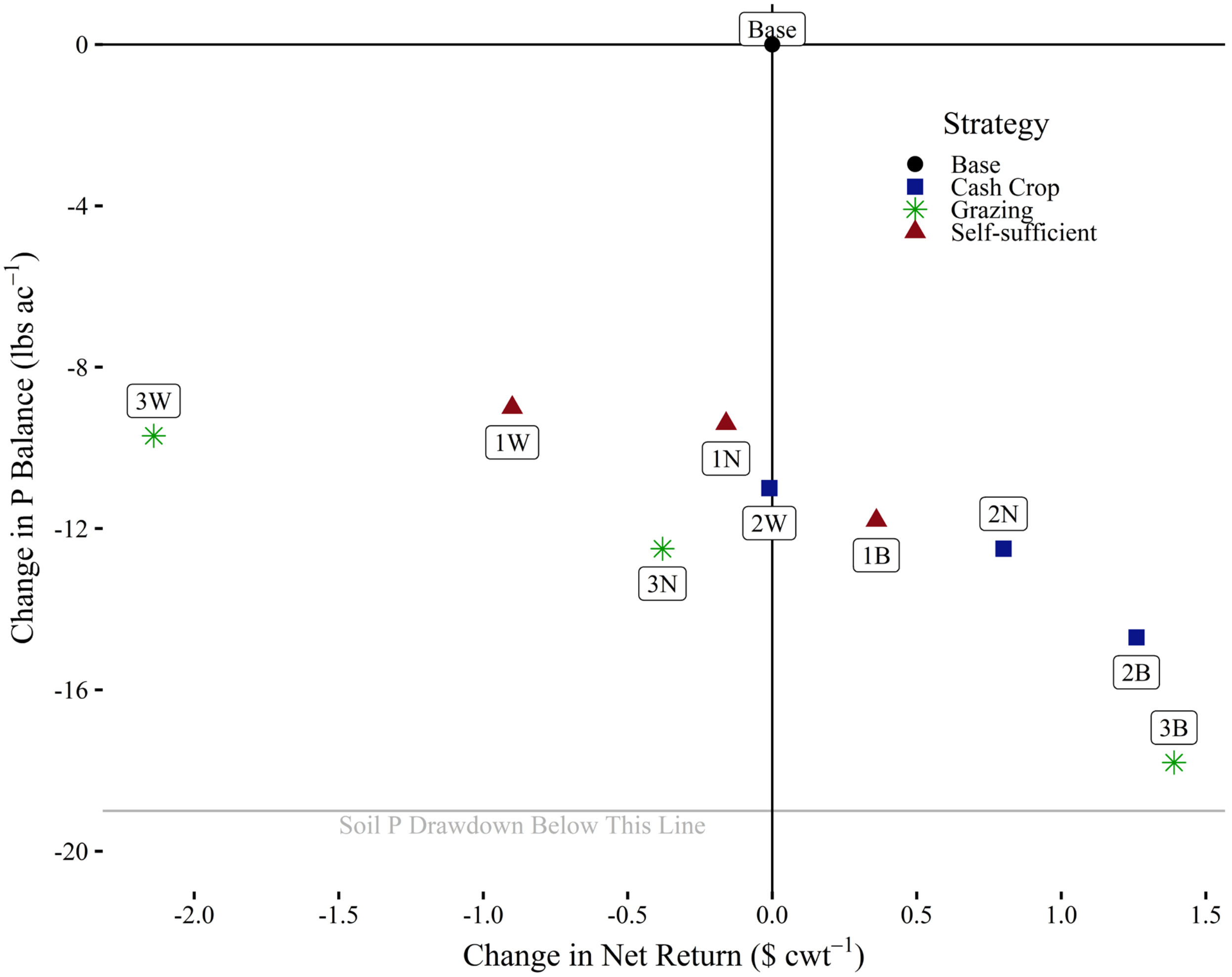

Figure 3-2. The relationship is shown between the change in P balance per acre and the change in farm net return for a small Virginia dairy farm. Baseline = current state of operation; Cash (Strategy 2) = expanding land base and growing corn grain for sale; Graze (Strategy 3) = expand and establish a grazing based system; Scale (Strategy 1) = expanding land base and scaling up homegrown feed production. The range in scenario outcomes are notes with letters: N = Neutral; W = Worse; B = Better.

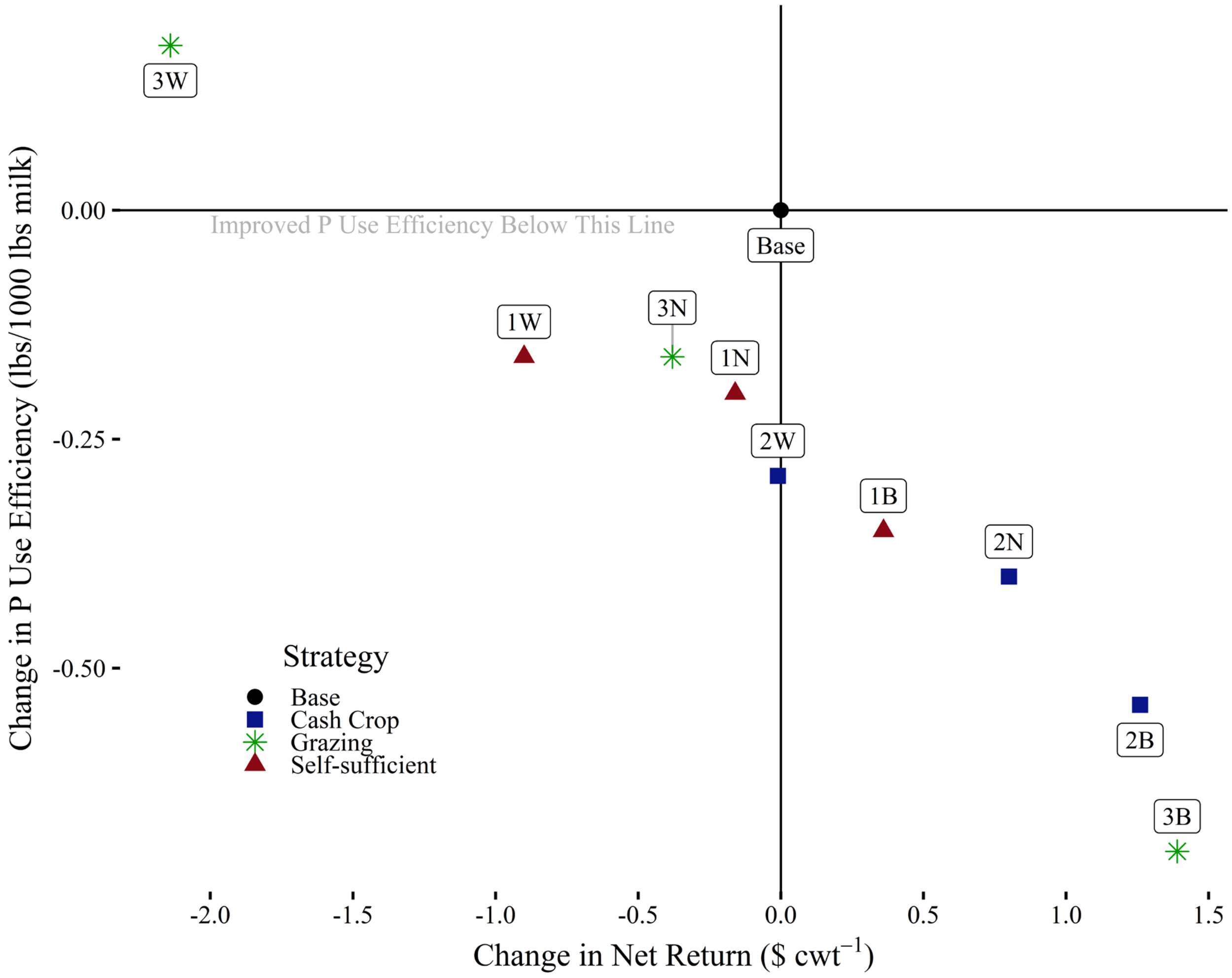

Figure 3-3. The relationship is shown between the change in P use efficiency and the change in farm net return for a small Virginia dairy farm. Baseline = current state of operation; Cash (Strategy 2) = expanding land base and growing corn grain for sale; Graze (Strategy 3) = expand and establish a grazing based system; Scale (Strategy 1) = expanding land base and scaling up homegrown feed production. The range in scenario outcomes are notes with letters: N = Neutral; W = Worse; B = Better.