Phosphorus mass cycling and balance in dairy farms: Case studies in Puerto Rico

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Abstract

Intensively managed dairy farms in Puerto Rico are suspected of being important contributors of phosphorus (P) in runoff that can reach surface-waters. A whole-farm P balance is a practical tool that can be used to estimate the net amounts of P retained within farms. In addition, knowledge of the internal mass-P cycling within farms (cows, pasture-lagoon, soils and forage) can be used to assess the relative risk of the on-farm agricultural practices to the environment and to identify management practices that reduce P accumulation in soils. Two dairy farms representative of feed and management practices in the Caribbean were assessed to describe internal mass-P cycling and to produce a whole-farm P balance. Farm A with an area of 58 ha had 120 lactating cows that rotationally grazed on improved tropical-grass pastures, and Farm B with an area of 310 ha had 482 lactating cows that were managed in semi-confinement, were fed silage and concentrate during the day, and were grazed only at night. Over 60% (DM basis) of all feeds consumed by dairy cows were imported to the farms, accounting for 71% and 81% of the P consumed in Farms A and B, respectively. The majority of the total P consumed by lactating cows (65% in Farm A and 75% in Farm B) was from commercial dairy grain concentrate, and the remaining P inputs were from grazed and cut pasture. Phosphorus in milk and animals sold (outputs) was 21% of total P inputs in Farm A, and 17.5% in Farm B. Dietary P concentrations, in both farms, exceeded by more than 60% nutritional recommendations of P. On an annual basis, there was an annual surplus (i.e., positive P balance) of 3,132 kg P farm⁻¹ (54 kg P ha⁻¹) and 18,290 kg P farm⁻¹ (59 kg P ha⁻¹) in Farms A and B, respectively. At current milk production levels the practices with the greatest impact potential for reducing soil P enrichment in dairy farms are reducing P inputs in feeds, improving P recycling by maximizing harvested pasture, and reducing or discontinuing fertilizing P additions to grazed pastures.

Key words: Whole-farm P balance; internal P cycling; Soil-test P; Water quality; Dairy cow P intake

1. Introduction

Milk production is the most important agricultural commodity in Puerto Rico accounting for 30% of the total gross agricultural income estimated at \$789 million in 2010-2011 (ORIL, 2012). Mean daily milk yield of lactating cows in Puerto Rico is about 16.3 kg d⁻¹cow⁻¹ and has not increased for decades, while in the continental United States milk yield has shown consistent annual increases and is now estimated at 33.0 kg d⁻¹cow⁻¹ (ORIL, 2012). Caribbean dairy farms are dependent on intensive feeding of concentrates because of the low nutritive value of tropical forages, decreased on-farm forage area availability, high stocking rates (SR), and high cost of land (Torres et al., 2009; ORIL, 2012). Concentrate feed intake is estimated to be over 50% of the total daily dry matter intake (Ruiz et al., 2008).

Ingredient availability to commercial feed-mills in the Caribbean is very limited, mainly by the high transportation costs and reduced diversity of feeds. The basic ingredients used by commercial feed-mills to formulate lactating cow concentrates are corn, soybean, and wheat middlings. Minor amounts of dried distiller grains and whole cotton seeds are used on a seasonal basis. A recent evaluation and analysis of commercial dairy concentrates in Puerto Rico indicated that most concentrates contained more than 40% wheat middlings (Oficina de la Reglamentación de la Industria Lechera, 2015 personal communication). Even so, cooperative efforts by local dairymen and nutrition experts have demonstrated that even with the limited availability of ingredients it is still possible to formulate economical and nutritive concentrates

1 without wheat middlings¹. In Puerto Rico dairies Torres et al. (2009) have shown that dietary
2 phosphorus (P) concentrations 87% higher than National Research Council recommendations
3 (NRC, 2001).

4 Greater P feed concentration and P mass intake is directly linked to increased manure P
5 concentration in local dairies (Sotomayor-Ramírez et al., 2003; Torres et al., 2009) and
6 elsewhere (Valk et al., 2000; Powell et al., 2002; Dou et al., 2003; Elizondo-Salazar, 2005). The
7 manure P is deposited to soils by grazing animal excretion and from manure holding-lagoons
8 during irrigation. Increased herd size, decreased land area for forage production, and higher P in
9 feeds and manure of local dairies have contributed to the accumulation of soil P beyond critical
10 agronomic levels in many dairy farms (Martínez et al., 2001; Ortega-Achury et al., 2007). Higher
11 soil test P concentrations in soils under pasture are linked to increased likelihood of higher P
12 concentrations in runoff and eventual surface water contamination (Sotomayor-Ramírez et al.,
13 2010; Ramírez-Ávila et al., 2011). Nutrients are usually significantly above background
14 concentrations in streams and rivers draining agricultural and urban areas (Dubrovsky and
15 Hamilton, 2010), and are primary contaminants of continental U.S. rivers/streams (USEPA,
16 2006). In Puerto Rico, although nutrients have not been officially listed as sources of impairment
17 (PREQB, 2012), high P concentrations have been observed in some surface waters (Martínez et
18 al., 2005; Sotomayor-Ramírez et al., 2011), especially where the prevalence of animal farm
19 operations in sub-basins increases (Ocasio et al., 2003).

20 It is thus important to evaluate site-specific dairy management and feeding practices
21 regarding their potential excess nutrient consumption and excretion particularly of P and
22 nitrogen. Sotomayor-Ramírez et al. (2003) documented large P surplus in dairy farms in Puerto
23 Rico. Results from this study were later supported by data from Torres et al. (2009) who

¹ Personal communication with local dairy producers.

provided site-specific evidence of excess dietary P from fourteen pasture-based dairy farms. This paper presents a detailed description of internal mass P cycling in conjunction with a whole-farm P balance in two tropical dairies with two management levels. This analysis will determine if P retention amounts in the farm are of concern and aid in identifying specific management practices that can effectively reduce the amount of P retained in the farm, and reduce the risk of environmental contamination.

2. Materials and methods

2.1. Description of sites

Two Holstein dairy farms located on the western (Farm A) and eastern (Farm B) regions of Puerto Rico were selected based on herd size and management style. Farm A has 58 ha of improved pastures (Table 1), mostly stargrass (*Cynodon nlemfuensis*), and minor extents of “malojillo” (*Urochloa mutica*) and “malojilla” (*Eriochloa polystachia*) in the lower and wetter areas of the farm. The dairy herd consisted of 201 animals of which 60% were lactating cows. This farm can be considered a typical local dairy relying on grazing for forage consumption. Mean daily milk production at the time of the trial was 19.6 kg cow⁻¹. Farm B has 310 ha of improved grass pastures. Mixed pastures consisted primarily of malojillo grass and star grass; with smaller extents of Bracharia (*Urochloa brizantha* cv Mulato). The total herd consisted of 1,289 animals, including 482 lactating cows. This is a large dairy (by Caribbean standards) using partial grazing (only at night), and feeding a mixed ration during the day. The lactating herd was divided into a low production (LP) group of 170 cows with an average daily milk production of 14.5 kg cow⁻¹d⁻¹ and a high production (HP) group of 312 cows averaging 25.9 kg cow⁻¹d⁻¹. Both farms were enrolled in the local Dairy Herd Information Association (DHIA) program and were

participants in United States Department of Agriculture, Natural Resources Conservation Service (NRCS) Conservation Plans. Animal weights were estimated based on 545 kg for lactating and dry cows, 227 kg for heifers (< 9 months), 136 kg for heifers between birth to 9 months of age, and 590 kg for the bulls. Stocking rate was calculated for each farm and/or group of animals based on animal units (AU), equivalent to 455 kg of live-weight.

2.2. Sampling and analysis of feeds and pastures

Farms were visited bi-weekly from May 2003 to February 2004. Feed samples were gathered from all feeds utilized in each herd and included commercial concentrates and purchased forages (grass hay, alfalfa hay, and silage). Feed concentrates and hay samples were collected directly from feed bins at feeding time. Pasture samples were taken from the next plot to be grazed on the day of the visit, and in Farm B, a different set of pasture samples were obtained for plots grazed by HP and LP groups. Pasture yield and availability was estimated by the use of a calibrated aluminum disk (Santillan et al., 1979) with pasture height and density as criteria to estimate yield. Estimates of grazed forage were obtained by sampling plots before and after grazing.

All feed and forage samples were placed in plastic bags and frozen for storage until ready for analysis. Samples were dried for 48 h in a forced air oven at 60°C, and ground through a 2-mm sieve for further analysis. All samples were analyzed for crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and nutrients (P, Ca, Mg, K, and Na) in a commercial laboratory (Dairy One, Ithaca, NY). Two samples of milk for P analysis were stored directly in plastic bottles and frozen until analysis by the dry-ash method (Ryan et al., 2001).

2.3. Soil, manure and lagoon sampling and analysis

1 Soil samples were collected from lactating-cow grazing plots at two different soil depths
2 (0 to 7 cm and 0 to 15 cm). Sampling at the shallow depth was utilized for evaluation of
3 environmental assessment (Gburek et al., 2000; Sims et al., 2000), and the other for agronomic
4 evaluation. Samples were air dried, screened through a 2-mm sieve and analyzed for pH and
5 available P by the Olsen method (Sims, 2000). Fecal samples were collected from 10 lactating
6 cows selected according to on-farm milk production records and days-in-milk to represent herd
7 profile. Fecal samples were taken directly from the cows' rectum to determine fecal P content
8 using a plastic insemination glove. Samples were kept frozen until analyzed for total P (Ryan et
9 al., 2001) and soluble P (Dou et al., 2002).

10 Farm A applied dairy manure-sludge from the waste-holding lagoon at monthly intervals,
11 distributed among 10 irrigation stations and 8 grazing paddocks. Farm B effluent was applied
12 three times per week using 40 irrigation stations distributed among 20 grazing paddocks.

13 Lagoon manure-sludge samples were collected on two occasions from within each lagoon
14 at 30-min intervals during the application periods and were mixed in a 20-L container (Crouse et
15 al., 2000). Subsamples were placed in 1-L plastic bottles and stored frozen until further analysis.
16 All samples were analyzed for pH and total P (Ryan et al., 2001). Additional samples were taken
17 of manure-sludge applied to grazing plots by placing five 20-L plastic containers in fields during
18 irrigation. The effluent collected in each container was combined and mixed to obtain a
19 composite sample. This composite was used to estimate P applied directly to grazing plots as a
20 separate fraction to that present in the lagoon. A 1-L sample was stored for pH determination and
21 analysis of total and soluble P, as before.

22 Total P analysis was determined by the ash method and analyzed by colorimetry using
23 the yellow color method of ammonium-vanadate and molybdate (Ryan et al., 2001). The soluble

P concentration in feces was determined diluting 1:10 (manure:water), shaking for one hour and analyzing by colorimetry as before (Dou et al., 2002). The P concentration in milk was determined as described by Morse et al. (1992). Potable water ingested by cows were only analyzed for total P as described before.

2.4. Whole-farm P balance

The whole farm P balance was determined following the model proposed by Van Horn et al. (1998). This model utilizes the differences between the mass of P entering the farm (inputs) and P leaving the farm (outputs) (Spears et al. 2003; Koelsch et al., 2010) and was used as part of the analysis of P management by establishing the amount of P retained at the farm level. Phosphorus inputs included that in commercial concentrate feeds, imported forages and in mineral fertilizers; while outputs included P leaving the farm in milk and in sold animals.

Beede and Davidson (1999) evaluated P excretion models and suggested that the simple model proposed by Van Horn et al. (1998) was the most appropriate for estimating the whole P balance. In an earlier study, Tomlinson et al. (1996) concluded that the simple whole farm model of inputs and outputs is as precise as models derived from excretion data. A possible reason is that published models do not take into consideration the lower digestibility of fiber and ration and limited availability of feeds in dairy production systems compared to same systems in the tropics. Thus, it was decided to develop the simple input-output model to determine P balance in the two farms.

2.5. Internal mass-P cycling

The internal mass-P cycling was done to accurately describe the movement of P from animals to lagoons and pastures, and was described using the animal (milking cows and other animals in the herd) specific P balance, the P in lagoons and that applied in effluent, and manure-

and fertilizer-P applied in pastures. Animal-specific P balance of lactating cows considered P inputs in pasture and commercial concentrates as well as consumption of other purchased feeds including hay, silage, and mineral supplements. The P concentration in water consumed by the animals in the farms was $< 0.05 \text{ mg P L}^{-1}$, thus, its contribution to the P input was considered negligible. Outputs included P in milk and that excreted in feces (balance of inputs not excreted in milk). The balance for non-lactating animals (dry cows, heifers, calves, and bulls) was estimated as the difference between consumed P in feeds and that utilized for growth and weight gain. A P content of 7.4 g kg^{-1} was assumed for weight gain and maintenance (Satter and Wu, 1999). Daily weight gains of 0.74, 0.68, and 0.54 kg were assumed for bulls, calves, and heifers, respectively. An additional requirement of 2.5 g P d^{-1} was allowed for fetal growth in pregnant cows in their last trimester. Estimated P needed for maintenance and lactation was calculated by assuming a 0.70 absorption coefficient as suggested by NRC (2001).

3. Results and discussion

3.1. Stocking rates

In Farm A, 120 dairy cows rotationally grazed on 23 ha divided into 14 paddocks. The overall SR was 3.5 AU ha^{-1} , distributed among 5.2 AU ha^{-1} for lactating cows and 1.9 AU ha^{-1} for dry cows and heifers (Table 1). Farm B had an overall SR similar to that in Farm A (3.4 AU ha^{-1}), but the SR differed greatly between the HP and LP groups of lactating cows with values of 10.4 and 5.7 AU ha^{-1} , respectively, and 2.4 AU ha^{-1} for dry cows and heifers. The lactating cows in the HP group only grazed 36 ha of pasture, regardless of available pasture land.

The SR is an important variable related to pasture utilization and yield that will have a large influence on the recycling and eventually in the accumulation of P in soil. Powell et al.

(2002) reported that low SR is associated with farms having small positive nutrient balances (input minus output > 0). These farms usually produce most of the forage necessary to satisfy the animal energy requirement and the remaining land can be used for other related activities such as the implementation of some best management practices. These authors suggested that SR values lower than 0.19 AU ha⁻¹ could be categorized as low and those greater than 1.68 AU ha⁻¹ as high. Approximately 70% of Wisconsin dairy farms surveyed had low SR with sufficient land to produce all the forage and nutrients needed to feed their lactating herds. Self-sufficiency in forage production generally indicates that the farm has sufficient land in use to effectively recycle feces and corresponding nutrients generated by the dairy herd. In comparison, the two farms evaluated in this trial (Farms A and B), are obviously in the high SR grouping. However, these SR are considered to be typical and comparable to most dairy farms in Puerto Rico (Torres et al. 2009; ORIL, 2012).

3.2. Feed P consumption

The mean P concentration in grazed forage was 3.9 and 3.6 g kg⁻¹ in Farms A and B, respectively (Tables 2 and 3). Our data are in agreement with P concentration in stargrass samples obtained from several local dairies that ranged from 1.8 to 4.8 g kg⁻¹ (mean of 3.7 g kg⁻¹) (Ruiz-Torres et al., 2008). However, our P concentrations in grazed forage are higher than Vicente Chandler et al. (1983) whom reported concentrations of less than 3.0 g kg⁻¹, even though pastures were fertilized with 100 kg of P ha⁻¹ yr⁻¹. From an agronomic perspective, the high P in pastures represents an opportunity to reuse P from soils during grazing which can potentially mitigate excessive P accumulation in soils (Cerosaletti et al., 2004).

Daily DM consumption in Farm A was 18.4 kg cow⁻¹ d⁻¹, with an estimated 38.6% coming from pasture, 11.4% from alfalfa hay, and 50.0% from commercial concentrate (Table

4). Daily DM consumption in the LP group of Farm B was $15.8 \text{ kg cow}^{-1}\text{d}^{-1}$, with an estimated 41% coming from pasture and 58.9% from commercial concentrate. For the HP group total daily intake was $16.8 \text{ kg cow}^{-1}\text{d}^{-1}$, with an estimated 23.8% coming from pasture, 17.9% from sorghum silage, 2.6% from mineral supplement, and 55.6% from commercial concentrate. Based on the chemical composition of sampled feeds, the weighted P concentration of the ration was 5.3 g P kg^{-1} in Farm A, and 6.0 and 5.7 g P kg^{-1} in Farm B for cows in the LP and HP groups, respectively. For 600 kg adult lactating cows producing between 10 and 50 kg of milk, dietary P recommendations are 2.1 to 4.1 g P kg^{-1} (NRC, 2001). Dietary P concentrations measured were at least 61% higher than recommended concentrations by the NRC (2001), based on milk production levels.

Estimated daily P consumption per cow was $97.2 \text{ g P cow}^{-1}\text{d}^{-1}$, with 71% coming from feeds imported to the farm (commercial concentrate and alfalfa hay) in Farm A. In Farm B, cows in the LP group consumed an estimated $95.2 \text{ g P cow}^{-1}\text{d}^{-1}$, with approximately 75% coming from the commercial concentrate. Cows in the HP group had an estimated daily P consumption of $96.1 \text{ g P cow}^{-1}\text{d}^{-1}$ of which 81% came from imported feeds (dairy concentrate, sorghum silage and mineral supplement) to the farm. The greatest source of P imported to the farm originated from commercial concentrate; which was 65 and 75 % of P consumed in Farms A and B, respectively. Dietary P concentrations reported by us are in the higher range of values reported in the literature (Powell et al., 2001; Dou et al., 2003), and strongly suggest that in these cases, dairy cows were excreting large amounts of P in feces.

3.3. *Phosphorus in feces*

The P concentration of feces (dry matter basis) were similar in the two farms, with mean values of 12.4 and 12.9 g kg^{-1} for Farms A and B, respectively (Table 5). However in Farm B,

the manure P concentration from cows in the LP group was 13.9 g kg^{-1} compared to 11.9 g kg^{-1} for the HP group, a 14.4% decline in the latter. This difference could be explained by the similar P intake yet lower milk production in the LP group. Our manure P concentrations are in the high range of values (6.7 and 12.8 g kg^{-1}) reported by Tomlinson et al. (1996). The high concentration of P in the feces of cows in our study is consistent with the high dietary P and the high P excretion reported in the two dairies.

Soluble P in feces is readily available for primary production in aquatic environments and can be a contributor to eutrophication of water bodies when it is a limiting nutrient for algal growth. Dou et al. (2002) concluded that the soluble P fraction in feces increases proportionally to the P concentration in the diet and suggest that a soluble P greater than 2 g kg^{-1} is indicative of high P concentration in the diet. In the present study, soluble P represented about 20 to 30% of the total P in feces (Table 5). These values are lower than what would be expected based on the high dietary P concentration in the diet, because the main source of P in the diet was wheat middlings which has a relatively high P concentration, presumably in organic form.

3.4. Internal mass P cycling

In Farm A the estimated amounts of P needed for maintenance and lactation (considering the efficiency of digestion) was $61.5 \text{ g P cow}^{-1}\text{d}^{-1}$ (Table 6). Total P excretion per cow was quantified at $77.7 \text{ g P cow}^{-1}\text{d}^{-1}$ ($28.4 \text{ kg P cow}^{-1} \text{ yr}^{-1}$). Thus 37% of the total P consumed was in excess of maintenance and lactation needs. In Farm B, the estimated amounts of P needed for maintenance and lactation was $49.9 \text{ g P cow}^{-1}\text{d}^{-1}$ for the LP group and $67.8 \text{ g P cow}^{-1}\text{d}^{-1}$ for the HP group. Total P excretion per cow was quantified at 80.6 and $70.2 \text{ g P cow}^{-1}\text{d}^{-1}$ for the LP and HP groups, respectively. Thus, P consumed by cows was 48% and 29% in excess of maintenance and lactation needs for the LP and HP groups, respectively. Phosphorus excretion was higher in

1 the LP group as a consequence of their lower milk production and lower requirements related to
2 intake.

3 The contribution of non-lactating animals (dry cows, heifers, calves, and bulls) to the
4 total farm P balance was quantified considering the P inputs in the concentrate and that
5 consumed in pastures (Table 7). In Farm A, pasture intake was estimated at 2% of live-weight,
6 and a 0.4 kg kg⁻¹ substitution rate of forage when concentrate was fed (Fike et al., 2003). Total P
7 consumption in the ration was 172, 40, and 26% higher than required (NRC, 2001) for bulls, dry
8 cows, and heifers, respectively. As a group, non-lactating animals had an estimated yearly
9 excretion of 815 kg yr⁻¹ (or 14.1 kg ha⁻¹yr⁻¹). This annual amount excreted was 53% in excess of
10 suggested nutritional requirements (NRC, 2001). Total P excretion on an areal basis by all
11 animals (lactating and non-lactating) was 72.7 kg ha⁻¹, with 81% being contributed by lactating
12 cows. In Farm B, P consumption by non-lactating cows was also in excess of suggested
13 nutritional requirements, being 173, 177, 175, and 114% higher than requirements for bulls, dry
14 cows, heifers and calves, respectively. As a group, these animals contributed the equivalent of 20
15 kg P ha⁻¹yr⁻¹. Approximately, 53% of the total P excretion was due to excess feeding in the
16 concentrates.

17 When considering the total farm P excretion allocation by the type of animal, 78% of it
18 was contributed by lactating cows with values between 30 and 32 kg cow⁻¹yr⁻¹. These values
19 were similar to those reported by Sotomayor-Ramírez et al. (2003) in modeled dairy production
20 systems in Puerto Rico. However, these results were higher than the range (19 to 35 kg cow⁻¹yr⁻¹)
21 reported by various authors (Van Horn et al., 1991; Powell et al., 2001; Spears et al., 2003) in the
22 continental USA. Published studies suggest that a high producing dairy cow, which are fed a diet
23 with adequate P levels should excrete approximately 21 kg cow⁻¹yr⁻¹ (Wu and Satter, 2000;

Powell et al., 2001). Our results demonstrate the relatively high P excretion rates of tropical dairy production systems, particularly due to the high P inputs from concentrates.

Of the total annual P feed input of 5,205 kg P in Farm A, about 80.8% of the P consumed by animals was retained in the farm (Figure 1). The herd P utilization efficiency (HPUE; P in milk/P in feed) (Spears et al., 2003) was 19.2%. About 62.6 % of the P retained was excreted directly to pasture by grazing animals, and was estimated at 2,639 kg P, or 45.5 kg ha⁻¹yr⁻¹ (Table 8), and rates were similar to estimates by Sotomayor-Ramírez et al. (2008) in the same farm. The remaining 37.4% of fecal P (estimated at 1,565 kg) was excreted near the holding pen, milking parlor, and other concrete surfaces and was channeled into the waste-holding lagoon. Application of P to pastures in the form of effluent was 895 kg P for an areal estimate of 15.4 kg P ha⁻¹yr⁻¹. The spatial variation of effluent added to particular fields will vary in accord with the scheduling of application and the distribution of field plots included in the irrigation scheme (Sotomayor-Ramírez et al. 2008). Annual total P inputs to soils were 3,135 kg P or 54.0 kg ha⁻¹yr⁻¹, and included the fraction excreted directly by grazing animals, that irrigated with the effluent, and that applied with the fertilizer. In this farm, 36.4% of the P applied to soils was reused in consumed pasture.

Of the total P feed input of 24,252 kg P in Farm B, about 82.4% of the P consumed by animals was retained in the farm (Figure 2). The HPUE was 17.6%. About 54% of the P retained was excreted directly to pasture by grazing animals, and was estimated at 10,876 kg P or 35.1 kg ha⁻¹yr⁻¹. The remaining 9,100 kg (45.6% of fecal P) was channeled into the waste-holding lagoon. Annual P input to soils from manure sludge was 8,482 kg P yr⁻¹ or 27.4 kg P ha⁻¹. Total P applied to soils from direct excretion during grazing, irrigated effluent and that in fertilizer was

62.8 kg ha⁻¹. About 7,447 kg P or 24.0 kg ha⁻¹ were removed by animals during grazing; this amounted to about 29% of all the P applied to the soils.

Both farms reported very low HPUE levels compared to the 44 to 66% reported for farms in Pennsylvania (Bacon et al., 1990). Direct excretion to pasture represented 69% of the initially P retained in Farm A vs. 54% in Farm B (Figures 1 and 2). This difference can be attributed to differences in grazing management, as cows in Farm B graze only at night. The more time spent grazing in Farm A resulted in a greater proportion of the retained P to be excreted directly to soils. These differences in grazing management, can also explain the higher proportion of total P inputs removed as pasture in Farm A (36.4 vs. 28.4%) than in Farm B. The reduced grazing time in Farm B resulted in less pasture consumption and less P recycled by grazing cattle. This resulted in 11.7% higher retention of P (58.8 vs. 54.1 kg ha⁻¹) in soils of Farm B, thus increasing the potential for P losses due to runoff from pastures. Sotomayor-Ramírez et al. (2006) reported that P losses in runoff from pastures amended with organic and inorganic P were in the range of 3.2 to 5 kg P ha⁻¹yr⁻¹. Of particular concern are paddocks receiving effluent irrigation or those used for grazing lactating cows which receive a disproportionately higher inputs of P, and will result in disproportionately high P input and potential losses to the environment.

3.5. Whole farm P balance

The main P import to the farms was that in concentrate feeds (Table 8). Phosphorus in inorganic fertilizer used on pastures was the second most important input source to the farm. The farm P outputs considered were that sold in the milk produced and that in the body of animals sold. Based on an assumed body weight of 454 kg and 7.7 g P kg⁻¹ of BW, the culling rate in Farm A was calculated at 30% (36 cows) and that in Farm B was 25% (121 cows). Farm-P intake in Farm A was 3,401 kg yr⁻¹, and 1,417 kg yr⁻¹ applied in the fertilizer for a total input

of 4,818 kg yr⁻¹. In Farm B, P intake was 16,804 kg yr⁻¹, and 7,573 kg yr⁻¹ in the fertilizer for a total input of 24,377 kg yr⁻¹. Output in milk and culled animals was 1,001 kg yr⁻¹ in Farm A and 4,276 kg yr⁻¹ in Farm B, resulting in a net P surplus (retention within the farm) of 3817 kg yr⁻¹ (or 65.8 kg P ha⁻¹), in Farm A and 20,101 kg yr⁻¹ (or 66.1 kg P ha⁻¹) in Farm B.

3.6. *Environmental soil test P*

Soil samples in Farm A were obtained from 11 grazing paddocks of which ten received dairy waste effluent from the lagoon. In the dairy effluent irrigated paddocks, two had soil test P (Olsen-P) in the “extremely high”, two were in the “very high” and six were in the “high” environmental soil test category as suggested by Sotomayor-Ramírez et al. (2004) (Figure 3). The probability of increasing P concentration in runoff increases with soil test P categorical rating of paddock (Ramírez-Ávila et al., 2011). Thus, most soils in paddocks receiving effluent in Farm A can be considered to be in the medium to high susceptibility category for P losses in runoff. The paddock that did not receive dairy effluent was near the agronomic soil test critical level (35 mg kg⁻¹) for Puerto Rico (Muñiz-Torres, 1992). In Farm B, only one of the ten paddocks sampled had soil test P levels that were below the agronomic critical level. Eight of the paddocks had soil test P in the “high” category and the remainder were in the “very high” category. All soil test P values increased in Farm B after two years of dairy-waste irrigation. This is evident when the soil P values of paddocks were compared with analysis of the same paddocks after two years of being irrigated with lagoon effluent.

In both farms, soils that received lagoon manure-sludge application had P concentrations above the critical agronomic level. Soils in paddocks that were farthest away from the lagoon tended to have the lower P concentrations. This pattern suggests that in spite of them having nutrient management plans, farmers tend to apply effluent more frequently and for longer periods

of time in paddocks closest to the lagoon and milking parlor. These paddocks are also preferably used by the milking herd. Most herds do not divide their milking cows into groups. In Farm B, we observed that the HP group used the closest paddocks.

Martínez et al. (2001) reported that in Puerto Rico dairies 75% of the soil samples obtained in plots where lagoon effluent was applied, P concentrations exceeded the critical agronomic level of 35 mg kg^{-1} . If current management practices are continued, a gradual and significant increase in soil P concentration should be expected (Rotz et al., 2002; Powers and VanHorn, 2001; Maguire et al., 2007). These increases are related to greater P loss in surface water run-off which can potentially contaminate nearby water bodies (Ebeling et al., 2002; Sharpley et al., 1994).

3.7. Implications

The feeding and management of P in dairy farms is a topic of concern to farmers and industry regulators (Maguire et al., 2007). Grazing area limitations in most farms of Puerto Rico decreases the area for P deposition and cycling. Limitations of quantity and quality of tropical forages increases the need to import feeds (energy and protein) to the farms. This could increase the potential for environmental impact, particularly if high levels of dietary P are fed and are not managed adequately.

Several management practices can be implemented to reduce the overall whole-farm P balance surplus and achieve P consumption levels near those recommended by NRC (2001). Some examples are greater use of pasture grown on-farm, use of feeds with lower P concentrations, decrease of animal SR to reduce overgrazing and improve pasture yield, and reduced application of fertilizers with high P concentration to pastures already containing high soil test P. One aspect related to reduction of feed P is by the establishment of controls on P

concentration in commercial feed formulations which can be achieved by reducing the proportion of by product feeds such as wheat middlings, which are less expensive than corn and soybean meal (SBM) yet have relatively higher P concentrations (NRC, 2001). Thus efforts to reduce dietary costs are associated with increased P concentrations. However, recent research (Rodríguez-Rosado, 2015) has shown that feeding high levels of dairy concentrates containing 50% wheat middlings resulted in a reduction of milk production of about 10% in early lactation cows compared to cows fed a concentrate not containing wheat middlings. The increased cost of associated with a reduction of wheat middlings in the diet may be offset by reduced milk production, and the use of high corn-SBM concentrates which are more energy dense and have the potential for proportionately greater milk production, could economically justify its use over less expensive concentrates (Rodriguez-Rosado et al., 2015). Such has been the case in that local dairymen and nutrition experts have been able to formulate economical and nutritive concentrates without wheat middlings.

The practice of applying lagoon manure-sludge in only a fraction of the total grazing area resulted in increases in P concentration of soils of the pasture plots receiving the effluent. Thus, expansion of lagoon manure-sludge application to areas that are environmentally viable can also reduce soil test-P concentrations. Another corrective practice which needs to be considered is manure export from farms having high P balance. The reduction in excess P excretion should increase the efficiency of P utilization and cycling, and reduce the magnitude of positive P balances.

4. Conclusions

1 Dietary P consumption for the lactating herd in the two farms evaluated exceeded by
2 more than 60% of nutritional P recommendations (NRC, 2001). This was mostly influenced by
3 the high concentration of P in the commercial concentrate fed and in the high proportion of
4 concentrate relative to milk production levels of the animals. The high concentration of P in
5 concentrates is in all probability is the result of the reliance on cheaper by-product feeds high in
6 P, particularly wheat middlings.

7 Despite them having different grazing management practices (greater confinement of
8 lactating cows in farm B), P excretion loads were similar in both farms, probably a consequence
9 of the similar total concentrate intake per cow. However, the HPUE was slightly higher for Farm
10 A probably due to the greater pasture dependence and lower milk production compared to Farm
11 B. In Farm B, despite the fact that the herd was divided into high- and low-production groups,
12 milking cows consumed similar amounts of concentrate. In both farms, the high positive P
13 balance increased soil test P and the risk of P runoff water enrichment. Soils in the “very high”
14 and “extremely high” environmental categorical rating were observed, primarily in plots irrigated
15 with manure-sludge from lagoons and in plots closer to the lagoon. Thus, fertilizer-P application
16 to manure-sludge irrigated pastures is not justified given their high soil test P values.

17 Results highlight the fact that peculiarities in management, feeding, and milk production
18 levels in tropical dairies compared to those in temperate climates result in higher P retention
19 relative to the land available for forage production. Possible corrective measures include
20 maximizing pasture yield and consumption which should increase pasture recycling and as a
21 consequence reduce the P retained in soils. However, this cannot be achieved unless P
22 concentration in the diet of lactating cows is reduced. Other suggested nutrient management
23 practices are rotational grazing, reduced SR, minimizing P fertilization and expansion of the land

1 area receiving manure-sludge effluent that could result in savings in fertilization costs and a
2 reduction in the potential for P losses to the environment.

3

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1 Table 1. General information of the farms.

	Farm A	Farm B
Animal inventory		
Milking cows ^a	120	482
Dry cows	29	200
Heifers	44	300
Calves	6	300
Bulls	2	7
Total	201	1289
Stocking rate		
Area of land in pastures (ha)	58	310
Animal units (AU)	205	1068
AU ha ⁻¹ , lactating	5.2	8.0
AU ha ⁻¹ , total	3.5	3.4
Milk production ^b	19.5	14.5 LP 25.9 HP

2 ^a Milking cows in Farm B were separated into 170 low producing cows (LP) and 312 high
3 producing cows (HP)

4 ^b Milk production in Farm B, is divided based on low production (LP) and high production (HP)
5 cows.

6

1 Table 2. Chemical composition of feed used in Farm A. All data are reported on a dry-matter
 2 basis.

	Alfalfa hay	Grass pasture	Lactating cow concentrate	High-fiber concentrate
Dry matter, %	91.8	91.0	94.5	88.5
Crude protein, g kg ⁻¹	192	161	201	213
ADF ^a , g kg ⁻¹	363	332	71	119
NDF ^b , g kg ⁻¹	479	669	188	280
TDN ^c , g kg ⁻¹	570	603	797	815
NEL ^d , Mcal kg ⁻¹	1.25	1.079	1.87	1.98
Calcium, g kg ⁻¹	16.8	6.0	13.4	13.5
Phosphorus, g kg ⁻¹	3.2	3.9	6.5	8.3
Potassium, g kg ⁻¹	25.8	26.5	11.6	2.4

3 ^a Acid digestible fiber
 4 ^b Neutral digestible fiber
 5 ^c Total digestible nutrients
 6 ^d Net energy of lactation
 7

1 Table 3. Chemical composition feed on a dry matter basis used in Farm B. All data are reported
 2 on a dry-matter basis.

Chemical Component	Sorghum silage	Grass pasture	Fish meal	High-fiber concentrate
Dry matter, %	90	91.1	92	88.2
Crude protein, g kg ⁻¹	90	158	667	241
ADF ^a , g kg ⁻¹	382	344	-	15.8
NDF ^b , g kg ⁻¹	558	658	-	316
TDN ^c , g kg ⁻¹	565	605	-	845
NEL ^d , Mcal kg ⁻¹	1.19	1.12	-	2.07
Calcium, g kg ⁻¹	5	3.4	56.5	15.6
Phosphorus, g kg ^{-1a}	2.3	3.6	5.4	7.7
Potassium, g kg ⁻¹	15.5	28.7	7.6	10.9

^a Acid digestible fiber

^b Neutral digestible fiber

^c Total digestible nutrients

^d Net energy of lactation

1 Table 4. Daily dry matter (DM) and phosphorus (P) intake of cows in Farms A and B.

	Farm A		Farm B			
			High producers		Low producers	
	DM	P	DM	P	DM	P
	kg cow ⁻¹	g cow ⁻¹	kg cow ⁻¹	g cow ⁻¹	kg cow ⁻¹	g cow ⁻¹
Milking cow concentrate	7.5	48.7	-	-	-	-
High-fiber concentrate	1.7	14.2	9.3	71.9	9.3	71.9
Grass pasture ^a	7.1	27.8	6.5	23.3	4.0	14.4
Alfalfa hay	2.1	6.6	-	-	-	-
Sorghum silage	-	-	-	-	3.0	6.9
Supplements						
Minerals	-	-	-	-	.20	1.6
Fishmeal					.23	1.2
Water		0.01		0.01		0.01
Total Intake	18.4	97.2	15.8	95.2	16.8	96.1
Dietary P concentration, g kg ⁻¹		5.29		6.02		5.73

^a Estimated by the difference before and after grazing (Santillan et al., 1979)

2
3

1 Table 5. Concentration of P in feces of cows by farm^a.

	Farm A		Farm B	
	Total P	Dissolved P	Total P	Dissolved P
	g kg ⁻¹ b		g kg ⁻¹	
Minimum	9.3	2.5	8.9	3.0
Maximum	14.7	5.4	16.5	5.1
Mean	12.4	3.4	12.9	3.0

2 ^a Based on a 10-cow sample in each farm.

3 ^b all data is reported on a dry-matter basis.

1 Table 6. Animal-specific phosphorus balance based only on contributions of milking cows by
2 farms.

	Farm A	Farm B	
		Low producers	High producers
Total P intake, g cow ⁻¹ d ⁻¹	97.2	95.2	96.1
P needed for maintenance ^a , g cow ⁻¹ d ⁻¹	23.5	20.4	21.6
P in milk produced ^b , g cow ⁻¹ d ⁻¹	19.6	14.6	15.9
Total P needs ^c , g cow ⁻¹ d ⁻¹	43.1	34.9	47.5
Dietary P requirements ^d , g cow ⁻¹ d ⁻¹	61.5	49.9	67.8
Excess dietary P ^e , g cow ⁻¹ d ⁻¹	35.7	45.3	28.3
Total P Excretion ^f ,			
g cow ⁻¹ d ⁻¹	77.7	80.6	70.2
kg cow ⁻¹ yr ⁻¹	28.4	29.4	25.6
kg ha ⁻¹ yr ⁻¹	58.7		41.9
kg farm ⁻¹ yr ⁻¹	3,401		12,992
Excess P excretion ^g ,			
g cow ⁻¹ d ⁻¹	35.7	45.3	28.3
kg cow ⁻¹ yr ⁻¹	13.0	16.5	10.3
kg ha ⁻¹ yr ⁻¹	27.0		19.5
kg farm ⁻¹ yr ⁻¹	1,563		6,029

3 ^a = 1.2 x dry-matter intake (kg d⁻¹) + 0.002 x body-weight (kg)

4 ^b = Milk production (kg d⁻¹) x 1.0g kg milk⁻¹

5 ^c = g P for maintenance + g P in milk

6 ^d = Total P needs / [70% (assumed efficiency of absorption)]

7 ^e = Total P intake minus dietary P requirements

8 ^f = Total P intake minus P in milk

9 ^g = Total P intake minus dietary P requirements

1 Table 7. Phosphorus balance of non-lactating animals by farms

	P Intake	P requirement ^a	Total P excretion	Excess P excretion	Excretion	Excess P excretion
	g animal ⁻¹ d ⁻¹				-----kg yr ⁻¹ -----	
	-----Farm A-----					
Bulls	53.5	21.4	48.0	32.1	35.1	23.5
Dry cows	46.2	20.9	43.7	22.3	462.7	236.5
Heifers	24.7	14.8	18.2	9.9	291.6	159.6
Calves	19.3	13.2	11.8	6.1	25.9	13.3
Total					815.2	432.9
(kg ha ⁻¹ yr ⁻¹)					(14.0)	(7.5)
	-----Farm B-----					
Bulls	41.8	24.1	36.4	17.8	92.9	45.4
Dry cows	36.5	20.6	33.9	15.9	2478.3	1738.9
Heifers	27.8	15.9	23.7	11.9	2591.5	1305.2
Calves	14.6	12.7	9.6	1.9	1048.8	204.8
Total					6211.6	3294.3
(kg ha ⁻¹ yr ⁻¹)					(20.0)	(10.6)

2 ^a P used for grow and pregnancy / 0.70 (efficiency of absorption)

1 Table 8. Flow of excreted phosphorus (P) by farms.

	Farm A	Farm B
	kg ha ⁻¹ yr ⁻¹	kg ha ⁻¹ yr ⁻¹
Fecal P		
Excreted directly to pastures ^a	45.12	32.58
Lactating cows	31.67	16.64
Non lactating animals	13.45	16.26
P collected in the lagoon ^b		
P applied to grazing plots	15.44	27.36
P retained in the lagoon	11.54	1.59
	(669.3 kg)	(618.9 kg)
P applied in fertilizer	24.43	24.43
Total P inputs to soils ^c	85.00	84.37
P in forage consumed (recycled) ^d	30.94	25.64
P retained in soils ^e	54.05	58.78
P retained in the farm ^f	65.59	60.72

2 ^a Estimates based on hours spent grazing on pasture daily.

3 ^b Estimates based on P content of manure sludge and amount of effluent applied to pastures.

4 ^c Total inputs = P excreted directly to soils + P applied to soils with manure effluent + P applied
5 in fertilizer

6 ^d Based on estimates of pasture consumed, disk measurement (ref), before and after grazing.

7 ^e Total P inputs – P consumed in forage

8 ^f P retained in soils + P retained in the lagoon.

List of figures:

Figure 1. Annual internal mass P-cycling for Farm A (58 ha), including P inputs (concentrate, imported hay, and pasture fertilizer) and outputs (P in milk and culled animals).

Figure 2. Annual internal mass P-cycling for Farm B (310 ha), including P inputs (concentrate, sorghum silage, and pasture fertilizer) and outputs (P in milk and culled animals).

Figure 3. Soil test P (Olsen) box-plot distribution in farms. Upper and lower boundaries of the box represent 75th and 25th percentiles, respectively; the dashed and solid lines within the box represent the mean and median values, respectively; upper and lower error bars represent the 90th and 10th percentiles, respectively.

Figure 1

FIGURES

Figure 2

Figure 3