Agricultural Systems 104 (2011) 551–561

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Identifying and controlling critical sources of farm phosphorus imbalances for Vermont dairy farms

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ARTICLE INFO

Article history:
Received 6 December 2010
Received in revised form 4 April 2011
Accepted 17 April 2011
Available online 13 May 2011

Keywords:
Dietary phosphorus
Farm modeling
Forage management
Mass nutrient balance
Phosphorus

ABSTRACT

Lake Champlain, located between Vermont, New York, and Quebec exhibits eutrophication mainly due to continuing phosphorus (P) losses from upstream nonpoint source areas. Several state and local agencies have initiated efforts aimed at assessing and identifying critical sources areas for P loss. To augment these efforts, accounting of farm P inputs (in purchased animal feed and fertilizers) and P outputs (in milk, meat, or off-farm sales of harvested crops or other products) is needed as a means of determining potential P build-up in farm soils. When farm P inputs exceed P outputs, P surplus occurs on the farm. This leads to potential soil-P accumulations and risk of P loss in runoff, negatively impacting the quality of receiving water bodies. In this study, a combination of farm record data and a model-based approach, using the Integrated Farming System Model (IFSM), was used to estimate farm P inputs and outputs, identify root causes of farm P imbalances, and explore viable P balancing strategies. Three Vermont dairy farms with varying farm systems (grass-based organic farm, fully confined farm, and a mixed system farm with high-producing confined dairy cows and grazing heifers) were studied. These farms were found to have P surpluses ranging from 5.5 kg/ha to 18.7 kg/ha on annual basis. This study also identified critical causes of P imbalances for each farm and suggested farm specific alternative strategies needed to address the P imbalances. By balancing farm P inputs and outputs, potential accumulation of soil-P can be prevented. As a result, maximum benefits can be obtained from land treatment measures implemented to control off-field P loss without the additional concern of continuing P build-up that could reduce their effectiveness.

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1. Introduction

Eutrophication of Lake Champlain, caused mainly by continuing phosphorus (P) losses from upstream nonpoint source areas, disrupts the lake's ecology and degrades domestic and recreational use and enjoyment of its waters. Lake Champlain is located mainly between the US states of Vermont and New York and but also extends into the Canadian province of Quebec. On the Vermont side, more than 90% of P entering the lake is estimated to come from nonpoint sources (Lake Champlain Basin Program, 2006, 2008). To address the excessive nonpoint P loadings to the lake and to meet water quality standards set as part of total maximum daily load (TMDL) requirements of the US Environmental Protection Agency (US EPA) and the Clean Water Act, the Vermont Agency of Natural Resources is required to develop approaches for identifying areas within priority watersheds that contribute disproportionally higher P loadings (Vermont Agency of Natural Resources, 2008). Identification of areas contributing disproportionally higher P loss, often called critical sources areas (CSAs), is needed in order to prioritize the allocation of limited resources in areas where they are most needed and where their impacts will be most cost-effective.

To support the State's effort in identification of CSAs for P loss, we have recently applied a model-based approach for identifying and quantifying CSAs for P losses in the Rock River watershed, an agriculturally dominated watershed draining into the Missisquoi Bay on the northeastern portion of Lake Champlain (Ghebremichael et al., 2010). A watershed-based model called Soil and Water Assessment Tool (SWAT; Neitsch et al., 2002) was used in this study. The study found that 80% of total P loss was generated from only 24% of the watershed area, validating the premise that all nonpoint P sources do not contribute equally to water impairment due to the variability in topography, soil, land use, and management. Watershed-modeling studies, such as the study by Ghebremichael et al. (2010), are useful in identifying and quantifying P losses from a landscape. However, the imbalance of farm P caused when P in farm inputs (e.g., animal concentrate, forage feed, and fertilizer) exceeds P outputs (e.g., milk, crops, and animals sold) was not accounted for in the watershed-based modeling approaches. In this region, agricultural activities consist primarily of dairy farming; agricultural crops, typically pasture, corn, and

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0308-521X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.agsy.2011.04.004

hay crops, are grown to support dairy farming. Most of the dairy farms in this region, however, are not able to produce adequate feed on their farm to meet the herd's feed requirement. Therefore, energy and protein feed supplements are imported, primarily from Canada and midwestern USA. In addition, most dairy herds in this study region, northeastern USA, are fed dietary P levels in excess of the published recommendations (Dou et al., 2003). Coupled with a production system that imports feed supplements, the practice of overfeeding P to dairy cows results in farms with a P imbalance problem: more P is imported to the farm than is exported. When farm P inputs exceed P outputs, P surplus occurs on the farm leading to a potential soil-P accumulation (Wang et al., 1999) and a risk of P loss to runoff, which may adversely impact water quality. Also, continuous build-up of P in soils may compromise the efficiency and lifespan of land treatment measures (such as contour farming and filter strips) applied to control off-field P transport to streams. Therefore, it is important to account for P inputs and outputs on farms as a means of estimating potential P accumulation in farm soils.

The objectives of this study were to estimate the P balance status of farms, identify components of farm systems causing farm P imbalances (surpluses), and explore alternative farm management strategies that could address the root causes of the farm P imbalances while ensuring long-term sustainability of farms. For this purpose, a farm-scale model, the Integrated Farm System Model (IFSM; Rotz et al., 2009) was employed using detailed farm record data on three study farms. This study aims to augment the ongoing efforts in identifying CSAs of P loss from landscapes by determining the potential P build-up in farm soils.

2. Materials and methods

2.1. Study area and farm descriptions

The study farms are located in Franklin County, Vermont (Fig. 1). These farms are situated in an agriculture-dominated area draining into the Missisquoi Bay (through the Rock and Missisquoi rivers) on the northeastern side of Lake Champlain. The climate of the area is humid with average annual precipitation of 1100 mm. Because of excessive nonpoint P inputs, the Bay is one of the Lake segments that does not meet the TMDL-specified target for P loading (Lake Champlain Basin Study, 1979; Lake Champlain Basin Program, 2006, 2008). In this region, dairy farming is the dominant agricultural production system and an important component of the Vermont economy. The average farm size in the county is 75 ha with about 50% of all farms owning fewer than 40 ha (USDA-ERS, 2009). Based on Vermont's farm size categorization, a farm with 0–199 cows is considered a small farm operation (SFO), 200–699 cows form a medium farm operation (MFO), and more than 700 cows constitute a large farm operation (LFO) (VAAFM, 2006, 2007). According to the 2007 USDA National Agricultural Statistics Service census of agriculture, eighty-two percent (82%) of farm operations in Franklin County are therefore classified as SFOs, 13% of farms are MFOs, and 5% of farms are LFOs. Overall, 42% of the cows in Franklin County are owned by small farm operations. We selected three dairy farms for this study based on variations in herd sizes and production systems and availability of data. These farms are identified in this paper as Farm-A, Farm-B, and Farm-C. Farm-A and Farm-B are SFOs and Farm-C is an MFO.

2.1.1. Farm-A

This farm produces certified organic milk by maintaining 75 mature Holstein dairy cows, and consists of 89 ha of crop area on predominantly medium loamy soils with slopes ranging from 3% to 8%. About 8 ha are used for corn silage production, and 81 ha are used for grass–legume mix forage production, which is harvested as a combination of wrapped round bales, chopped haylage, and intensively managed rotational grazing. Oats and wheat are used as a first year nurse crop in reestablishing the grass–legume mix. This farm has been producing certified organic milk since 2003. The average milk yield of the cows housed in a stanchion barn is 7258 kg/cow/year.

In addition to the 75 mature cows, the farm keeps 20 heifers <1 yr old and 20 heifers >1 yr old. All animals on the organic farm are grazed during the May to October grazing season using intensive rotational practices. Lactating cows are fed with corn silage, grass–legume mix, and a purchased energy feed and mineral supplement. The farm meets the protein requirements of the cows using the on-farm produced grass–legume forage. About 40% of the manure produced on the farm is used to establish the first year grass–legume and nurse crops, and the remainder is spread on fields following hay harvesting. This farm uses no chemical fertilizer.

2.1.2. Farm-B

This farm maintains 135 mature Holstein dairy cows and consists of 146 ha of crops on predominantly deep and medium clay loam soils with slopes ranging from 3% to 15%. In a typical year, only about 85 ha of the 146 ha are put in forage production mainly due to logistical limitations (resources, time, and labor). Crops grown on the farm include corn for silage (51 ha) and grass–legume mix (34 ha). Corn silage produced on farm is used as feed on the farm and also sold to bring extra cash income to the farm.

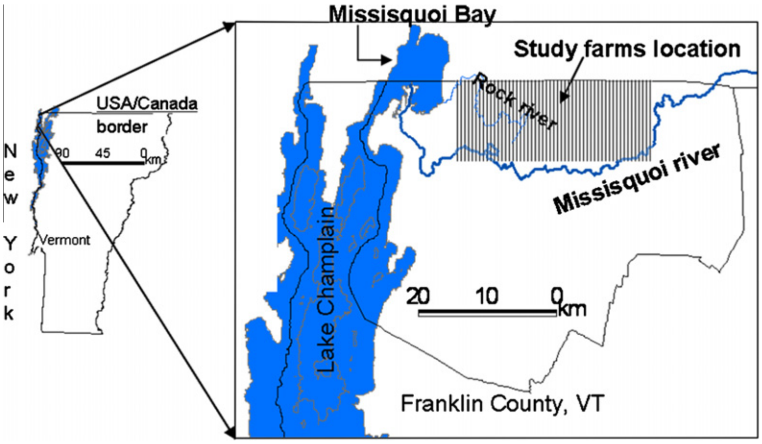

Fig. 1. Location of Lake Champlain, Missisquoi Bay, and general location of the study farms in Franklin County, Vermont.

On average, the farm sells 327 tonnes DM of corn silage annually. The farm uses strip cropping and contour plowing to minimize erosion losses of sediment. The cows are housed in a tie-stall barn year round. The average annual milk yield of the cows was estimated to be 8165 kg/cow. The cows are fed a mixed ration of on-farm produced grass–legume mix hay and corn silage, corn meal, soy meal, canola and citrus mix, and minerals and vitamins mix. In addition to the 135 mature cows, the confinement farm maintains about 38 heifers <1 yr old and 15 heifers >1 yr old. Manure produced on the farm is stored mainly in earthen pits during winter months when manure spreading is banned. About 70% of the manure produced on the farm is applied to corn fields and the remaining manure is applied to the grass–legume mix fields. In addition, corn receives starter fertilizer of 12 kg/ha nitrogen, 24 kg/ha phosphate, and 24 kg/ha potash, and a side-dress of 72 kg/ha nitrogen fertilizer.

2.1.3. Farm-C

The farm maintains 290 mature large Holstein dairy cows and consists of 184 ha of crop area on predominantly medium clay loam soils with slightly higher rock content and steepness compared to the two previously described farms. Crops grown on the farm include corn for silage (17 ha) and grass mostly for hay (167 ha). The soils and topography have been described by the farm manager as being "terrific for growing grass, but marginal for corn." In the future, the farm plans to phase out corn silage production and produce grass-based forage only, and purchase corn silage and other feeds as needed. All farm operations (e.g. tillage, forage harvesting, storage, and others) are custom operated because the farm does not own any farm equipments. The farm keeps 290 large Holstein cows in a free stall barn. These cows are fed a ration consisting of on-farm produced grass hay and corn silage, and supplemented with purchased corn silage, cotton meal, fine corn meal, high moisture corn, dried distillers grain, and a minerals and vitamins mix. In addition to the 290 mature cows, this farm maintains about 100 heifers <1 yr old and 90 heifers >1 yr old all housed in the barn in winter. Older heifers are grazed in the summer within rotating paddocks. Lactating cows are managed for a high milk yield averaging 11,340 kg/cow annually. Manure produced on the farm is stored in a bottom loaded lagoon. Ten percent of this manure is spread on corn, 80% on grass, and 10% is exported off-farm to other neighboring farms. In addition, corn fields receive starter fertilizer equivalent to 2.5 kg/ha nitrogen, 5 kg/ha phosphate, and 2.5 kg/ha potash, and a top-dress of 72 kg/ha of nitrogen.

2.2. Model description

The model selected for this study is called Integrated Farm System Model (IFSM; Rotz et al., 2009). The IFSM model is a comprehensive farm-scale model that simulates long-term environmental impact and farm profitability for various technologies and management strategies applied to a farm system. The model integrates models of crop growth, harvest, storage, feeding, animal (dairy or beef) production, and manure handling systems to determine the long-term performance and environmental and economic impacts of a farm enterprise. IFSM has been widely used in evaluation of farm planning strategies mainly in temperate regions of Northeastern and Central USA (e.g. Andersen et al., 2001; Rotz et al., 1999a, 2002; Ghebremichael et al., 2007).

The IFSM model requires three input data files (farm, machinery, and weather) to represent a typical farm system. The farm input data consist of detailed information that describes a farm enterprise, including crop types and their area, soil type and slope, fertilizer and manure applications, animal type (Holstein, Jersey, and others), number of cows of different ages, feeding information, milk production level, manure handling, storage, and application methods, equipment (tillage and machinery) and structures used, and prices of farm commodities produced, labor, custom operations, purchased feeds, and farm products sold off-farm. The machinery input file contains data concerning the machinery used, including parameters related to machine type, size and associated costs. Finally, the weather required by the IFSM model includes daily values of total precipitation, maximum and minimum temperatures, and solar radiation. The IFSM allows simulation of up to 25 years of weather data for a farm system.

The model is comprised of different components that help estimate potential nutrient accumulation and loss to the environment, farm performance, and profitability. The environmental component of IFSM predicts nutrient balances (P, nitrogen, and potassium) as well as off-farm erosion and nutrient losses. The farm P balance in the model is calculated by considering the import of P in feed and fertilizer and the export of P in milk, animals, and crops. The quantity and characteristics of P produced in the manure are calculated as functions of the quantity and P content of the feed consumed. In other words, P that is consumed but not used within the body for maintenance, growth, milk production, or reproduction will be excreted directly in the manure. The IFSM model evaluates the performance of a farm enterprise by predicting crop yield and quality, on-farm feed, milk, manure produced, feeds sold and supplemental feeds purchased, and resources expended, such as labor, fuel, and equipment use. The economic component of IFSM uses a simple enterprise accounting of production costs and incomes to compute net-return of a farm enterprise. The production cost includes costs of crop production, harvest, storage, feeding, and other production-related activities. The farm income includes receipts from sales of milk, animals, and crops. A complete description of the model and model components can be found in the IFSM model user manual (Rotz et al., 2009).

2.3. Farm modeling and verifications

To perform P accounting of farm inputs and outputs for each of the study farms, farm and machinery input files were created in IFSM using detailed farm record data. For each farm, these data were obtained from farm record data gathered by a staff member in the University of Vermont Extension Service (personal communication: Dr. Heather M. Darby, agronomist, University of Vermont Extension – Northwest Region, Saint Albans, VT, 2009).

IFSM predictions of crop production, feed use, and manure production (among others) were simulated over 25 years of weather obtained from the closest National Weather Service (NWS) Cooperative Observer Station in Enosburg, VT. To achieve an acceptable match between farm record data and model predictions of crop production, values adjustment for two model parameters were needed. First, the IFSM yield factor, which governs the crop growth rate curves and resultant yields, was adjusted until average predicted yield and nutrient content values were closely matched the farm record data. Second, the IFSM forage feed-level was adjusted by constraining the feed rates for energy and protein concentrates per cow per day. The feeding limit values used for energy and protein concentrates were based on typical feed rate data obtained from sample rations gathered by Dr. Heather M Darby (personal communication, March 2009). The model user can set a target milk production level that is only maintained when the nutritive value of available feeds is sufficient to meet nutrient requirements. By considering user-defined milk production targets and constraints on the maximum amounts of concentrate feed (energy and protein) rate per cow per day, the linear ration optimization program in the model (Rotz et al., 2009) obtains maximum herd milk production with minimum cost rations. Limiting these feed concentrates also forces the model to utilize more available farm silage and hay and maintain the relative proportion of the different types of supplemental feeds without exceeding the typical daily feeding rate of each supplemental feed. Finally, the model allocates and plans daily feed rations based on the nutrient contents of the feeds and by making sure individual animal requirements for maintenance, growth, and milk production are met.

After adjusting model parameters and matching predicted and farm record values for on-farm produced feed and daily feed rations, we then compared model-predicted total amounts of feed utilized on the farm, feed purchased from off-farm sources, and extra feed sold by the farm with their respective farm record data. Acceptability of the model predictions was determined based on actual representations of farm records, that is, when actual data is close to the modeled long-term mean values or falls within the standard deviation from mean value.

IFSM predicts P balance as a difference between farm P inputs and P outputs. That is, the model accounts for P in both farm inputs (such as, fertilizer, feed, and manure), and farm outputs (such as milk, crops, animals sold, manure or other outputs). Once the modeled farm inputs and outputs containing P are closely matched to actual farm data and the P concentrations of these inputs and outputs are represented well in the model, modeled P balance is assumed to be a close representation of the farm's P balance.

Verification of predicted economic variables focused on the most important economic factors (i.e., cost of feed purchased, income received from milk sales and a few others, which may be needed in the analysis of alternative management strategies). For other economic parameters, such as costs of labor, custom operations, equipment (tillage and machinery) and structures, typical costs were assumed. Total farm net-return value presented for each farm, therefore, does not necessarily reflect the actual farm-return data. This is done mainly to maintain confidentiality of the farmers' economic records and also due to the lack of detailed economic data. Note that the economic data analysis was included in the study to present the relative change in each farm net-return resulting from implementing different management strategies. Thus, comparisons of economic performances can be made for different strategies employed within an individual farm, but comparisons should not be made across/between the three study farms. Such analysis is beyond the scope of this study.

2.4. Determination of farm phosphorus imbalance

Farm P balance is estimated in the model by subtracting the amount of farm P exported from the amount of farm P imported in all farm system components. That is, the farm P balance is calculated by subtracting P in farm outputs (such as milk, crops, animals sold, manure or other outputs) from P in farm inputs (such as, fertilizer, feed, and manure); where, total P input (kg) = input (kg) × P concentration, for all farm input P sources; total P output (kg) = output (kg) × P concentration, for all farm output P sources. If the amount of P imported to the farm exceeds the amount exported off the farm, a P imbalance (surplus) is identified. For farms with P imbalances, farm components were then examined to identify critical farm components that are potentially causing the P imbalance problem. When farm P imported exceeds P exported, P is expected to accumulate in the farm system, particularly in soil of the farm fields. Hence, farm P balance estimation is used as a means of determining the potential P build-up in farm soils. The accumulation of excess P in the fields increases potential P loss in runoff.

2.5. Alternative farm management options and modeling

Once the critical P imbalance problems and their causes were identified, management strategies that had the potential to address the imbalance while maintaining farm profitably were explored and then evaluated using the IFSM model. Unlike most traditional pollution control practices, controlling farm P imbalances requires strategic changes in farm systems. Because each study farm was different, extension personnel were involved with developing alternative farm management strategies that were specific to each farm (Table 1). Management strategies were selected based on several important factors, including the extent of the P imbalance problem, farm-specific plans for the future, the potential effectiveness of strategies in directly targeting the root cause of P imbalance problem, and the potential economic viability of strategies.

The first strategy explored was to balance dietary P levels in dairy cows. P requirement guidelines for dairy cattle in the US are available from the NRC publications (NRC, 2001). The NRC recommends that the typical dairy cow diet contain between 0.32% and 0.38% P, depending on milk production of the animal fed. Depending on each farm cow's dietary level, a farm strategy of balancing dietary P levels to the NRC-recommend values was implemented and assessed (Scenario I; Table 1). The strategy involved decreasing the P content of imported mineral dietary supplements to minimize overfeeding of P. Studies have shown that reducing dietary P levels to match the NRC recommendations reduces both purchased feed P imports to a farm and P excreted in manure (Ebeling et al., 2002; Dou et al., 2002; Cerosaletti et al., 2004; and Ghebremichael et al., 2007). No negative effects related to milk production and animal production performance are expected from imposing this strategy as long as the dietary P is properly balanced to the cow's requirement (Wu and Satter, 2000; Wu et al., 2001). Also, recent studies (Sharpley et al., 2007; George et al., 2008) have emphasized the importance of implementing comprehensive P management strategies that begin with precisely balancing dietary P in animal production. This strategy also requires relatively small change in a farm system and has a direct benefit in reducing P imports (and P imbalances) and costs associated with supplemental P feed purchases. Thus, the strategy of balancing dietary P levels was considered for all study farms.

Table 1
Simulated farm management scenarios for each study farm and description.

Scenario	Description
Farm-A	
Baseline	Current farming system; conditions before management changes
Scenario I	Dietary phosphorus reduction to match NRC recommendations
Scenario II	Scenario I + corn land converted to high-quality forage (grass–legume mix) production
Farm-B	
Baseline	Current farming system; conditions before management changes
Scenario I	Dietary phosphorus reduction to match NRC recommendations
Scenario IIa	Scenario I + grow canola seed to be used as feed source on the proportion of corn area used for silage production for sale under baseline
Scenario IIb	Scenario I + grow high-quality forage (grass–legume mix) on the proportion of corn area used for silage production for sales under baseline
Scenario IIc	Scenario I + keep the baseline corn silage production for sale + grow more high-quality forage (grass–legume mix) on the under utilized area of the farm
Farm-C	
Baseline	Current farming system; conditions before management changes
Scenario I	Dietary phosphorus reduction to match NRC recommendations
Scenario IIa	Scenario I + corn land converted to high-quality forage (grass–legume mix) production
Scenario IIb	Scenario IIa + rent and expand land to grow high-quality forage (grass–legume mix)

Other farm strategies included expanding and increasing the productivity of homegrown-forage and/or grains on the farm as an alternative to purchasing protein and energy feed supplements (Scenarios II, IIa, IIb, and IIc; Table 1). These strategies focus on minimizing purchased feed, a potential source of excess nutrients, by promoting the cultivation and production of feed on the farm. Depending on each farm's situation with regard to land availability and crop suitability, on-farm forage productivity was increased so that more feed could come from homegrown feeds, decreasing the amount of purchased feed required. Thus, as stressed by Lanyon (1992) and Ghebremichael et al. (2008), recycling and re-use of P on the farm can be promoted by the increased productivity of on-farm forage. For a farm with insufficient land area, increased forage productivity was sought on additional rental land, extra space that presumably can also be used for manure application.

Alternative farm management strategies were simulated in the model by changing appropriate model input parameters. For example, for farms with excess P feeding rate, the P intake by animals in the model was set to the animal group P requirements following NRC-recommended values. Balancing dietary P to the animal requirement is expected to minimize overfeeding of P and to decrease manure P nutrient excretion. Because mineral P supplement is fed to cows mixed with vitamins, salt, and other micronutrients, dietary mineral P was reduced in the model until the dietary P matched to the NRC-recommended P levels while maintaining other feed nutrient requirements of cows. In addition, when forage productivity is increased, corresponding increase in the amount of forage fed to each cow was required. The increase in dietary forage was done in the model by selecting a high-forage diet option. When the model is set at high-forage diets, the maximum amount of forage is consumed, while meeting the energy and protein requirements with supplemental feeds and maintaining good rumen function (Rotz et al., 1999b). For a farm requiring an additional rental land, the scenario was simulated by specifying the area and rental cost rates. Because cost of crop rental land data specific for Vermont was not available, the 2009 USA average rental land price of $245 per hectare ($99 per acre; USDA-NASS, 2009) was assumed as a conservative cost estimate.

3. Results and discussion

3.1. Baseline feed production and utilization

Average crop yields and nutrient contents as predicted by IFSM and the data gathered from the farms are presented in Table 2. IFSM-predicted crop yields and nutritive contents represent average values based on simulations over 25 years, with each year predicted as a separate observation. Predicted crop yields are measured in tonnes DM/ha. The nutritive contents of crops, crude protein (CP), and neutral detergent fiber (NDF) are measured as percent of dry matter (DM). Both CP and NDF factors are forage quality indicators.

IFSM predicted 25-year average yields and nutrient contents of the grass–legume mix and corn silage, obtained by adjusting the model yield factor (controlling crop growth rate curves and resultant yields), were closely matched to actual average yield data obtained from farm records of the three farms. For example, predicted grass–legume forage yields for Farms A, B, and C, 9.0, 11.4, and 9.0 tonnes DM/ha, respectively, are closely matched those of the farms' average recorded yields of 10.0, 11.2, and 11.2 tonnes DM/ha. Similarly, the predicted corn silage yields of

Table 2
Actual farm data and Integrated Farm System Model (IFSM)-predicted annual feed production, purchases, and milk production levels.

	Farm-A		Farm-B		Farm-C	
	Actual[a]	Predicted[b]	Actual[a]	Predicted[b]	Actual[a]	Predicted[b]
Crop productivity						
Grass–legume/mix yield tonnes/ha	10	9	11.2	11.4	11.2	9
Area, ha	81	81	34	34	167	167
CP, % of DM	20.9	20.4	22	21	17	17
NDF, % of DM	43.9	43	52	49.3	51	52
Corn silage yield tonnes/ha	11	10	16.8	15.9	14.6	13.7
Area, ha	8	8	51	51	17	17
CP, % of DM	N/A	4.3	7.3	7.3	7.3	8.3
NDF, % of DM	N/A	49.4	42	43.6	43	43.8
Total farm area, ha	89	89	146	146	184	184
On-farm-produced forage						
Grass–legume, mix, tonnes DM	299	284(SD = 29)	181	193(SD = 18)	1037	914(SD = 181)
Corn silage, tonnes DM	62	58(SD = 5)	778	734(SD = 105)	222	190(SD = 37)
Grazed grass forage, tonnes DM	152	140(SD = 15)	–	–	218	193(SD = 12)
Corn silage sold, tonnes DM	0	–	327	300(SD = 148)	–	–
Feed purchased						
Corn silage purchased, tonnes DM	–	–	–	–	599	678(SD = 110)
P,% of DM			0.22			
Energy supplement	Organic grain mix	Corn meal/citrus	Corn meal			
Tonnes DM	181	154(SD = 27)	163	164(SD = 6)	274	270(SD = 18)
P, % of DM	0.41		0.26			0.35
Protein supplement	–	–	Soy meal	Cotton seed meal		
Tonnes DM			163	163(SD = 4)	132	129(SD = 12)
P,% of DM			0.71		0.26	
Protein supplement			Canola meal	DDG		
Tonnes DM			65	64(SD = 8)	511	441(SD = 18)
P, % of DM			1.03		0.6	
Salts and P mineral, tonnes DM	6	5(SD = 0)	11	9(SD = 0)	17	21(SD = 1)
P, % of DM	7.7			7.7		7.7
Milk production, kg/cow	7258	7258(SD = 0)	8165	8165(SD = 0)	11,340	11,340(SD = 0)

N/A = data unavailable; SD = standard deviation; DDG = distilled dried grain; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; P = phosphorus.
[a] Average farm record data.
[b] IFSM-predicted data.

10.0, 15.9, and 13.7 tonnes DM/ha for Farms A, B, and C, respectively, closely matched the average recorded yields of 10.0, 16.8, and 14.6 tonnes DM/ha. Predicted forage qualities also closely matched values obtained from farm's forage analysis data. Even though predictions of corn silage quality (CP and NDF) for Farm-A could not be verified due to the absence of farm record data, they were in agreement with the "very low quality" description used by the extension personnel who gathered the farm data. The low yield and poor quality of corn silage produced is likely due to absence of use of any chemical fertilizer (only manure was applied to corn crops). In fact, as previously mentioned, the farmer plans to phase out the poor yielding corn production for the next crop production year.

Other components of the farm system verified included average daily diet compositions and total feed, forage portion of diet, dry matter intake (DMI), and P content of the total ration (Table 3). In Table 3, IFSM-predicted average daily rations are presented for a randomly selected year. For Farms A and C, sampled farm feed records, representing a typical ration mix for the non-grazing period, are presented in Table 3 (in parentheses) for comparison purpose. Feed ration data for Farm B was unavailable. Overall, predicted total daily dry matter intake (DMI), percent of forage feed fed, and forage DMI per body weight for lactating cows were comparable to actual farm data and could be expected for the animal size and milk production levels of the farms. Based on NRC-recommended data, for cows with a milk production level of 27–35 kg/day and animal body weight of 600–650 kg (NRC, 2001), average DMI ranges between 19 and 20 kg/cow/day. The average body weight of lactating cows of the Farm-A, for example, was 601 kg and the average milk production level of the herd was 27 kg/cow/day. Therefore, the predicted DMI of 19.8 kg/cow/day for lactating cows (Table 3) was reasonably within the NRC-recommended values and close to the actual feed data gathered from the farm. This also holds true for the other two farms. These results indicate the capability of the IFSM to realistically represent cows' rations for these farm systems. Also, IFSM-predicted dietary P levels of the farms were close to the P levels calculated from the actual ration data. Daily P intake of cows for Farms A, B, and C, were 81, 92, and 111 g, respectively (0.41%, 0.48%, and 0.49% of diet DM; Table 3). On average cows in Farms A, B, C, respectively were fed 6, 19, 25 g more P than required, and these are in excess by 8%, 26%, and 29% when compared to the NRC-recommended P levels (0.38% of DM ration; NRC, 2001).

Moreover, for the milk production levels, IFSM-predicted amounts of feed produced, purchased, and utilized in the cows' diet compared well with actual farm metrics for all farms (Table 2). Based on farm data records, an average of 327 tonnes DM of corn silage was sold annually from Farm-B under baseline conditions, whereas Farm-C bought 599 tonnes of corn silage annually. The long-term predicted 300 tonnes DM corn silage sold annually from Farm-B and the 678 tonnes DM bought by Farm-C were, therefore, comparable to actual values. Also, IFSM-predicted amounts of grazed grass forage from Farms A and C compared well with farm estimates. To satisfy animal needs and maintain milk production, cows are fed with purchased supplemental feeds when insufficient feed is produced on the farm. Model-predicted total annual purchased supplements (energy, protein, and minerals and vitamins mix) for Farms A, B, and C of 159, 400, and 824 tonnes, respectively, closely matched those of the farms' average recorded supplemental feeds of 187, 402, and 834 tonnes purchased (Table 2). Actual P concentrations of purchased feed supplements that are used as inputs into the model are included in Table 2. Note that accurate model representation of feed inventory (purchased and produced on-farm) was one of the key aspects used in determining farm P balance.

Table 3
Integrated Farm System Model (IFSM)-predicted and actual data on average daily diet composition of lactating cows during the non-grazing season for the three study farms.

Feeds parameters	Farm-A	Farm-B	Farm-C
Hay and silage, kg/day	12.1(13.0)[a]	9.9	12.3(13.3)
Energy supplement, kg/day	7.5(6.4)	4.1	3.2(3.9)
Protein supplement, kg/day	–	5.0	6.8(6.4)
Minerals and vitamins, kg/day	0.17(0.19)	0.2	0.26(0.28)
Total daily feed fed, kg/day	19.8(19.6)	19.2	22.6(23.9)
Forage portion of diet, %	61(67)	52	55(56)
Average mature cow body weight, kg	611(601)	673	673(673)
Dry matter intake(DMI), % body weight	3.2 (3.3)	2.8	3.3(3.5)
Forage DM intake, % body weight	2.0(2.2)	1.5	1.8(2.0)
P fed, g/day	81.2(80.4)	92.2	110.7(119.5)
P content of total ration, % DM ration	0.41(0.41)	0.48	0.49(0.50)

[a] 12.1 = predicted value for a randomly selected simulation year, 13.0 = an estimate diet acquired from farm; P = phosphorus.

3.2. Baseline farm phosphorus balance

Predicted net-P balances of the study farms under baseline conditions are presented in Table 4. As noted previously, IFSM calculates farm P balance by subtracting farm nutrient P exports (in milk, animals, and crops) from nutrient P imports (in feed supplements, crops, and fertilizer). Positive value in net P balance implies that more P is being imported onto the farm than exported off the farm. Based on the modeling analysis, Farm-A (*75 mature cows with 7275 kg/cow/year milk production level and 89 ha of farm land*) was found to have the lowest predicted annual P imbalance of 5.5 kg/ha. Farm-B (*135 mature cows with 8165 kg/cow/year milk production level and 146 ha of farm land*) had a predicted annual P imbalance of 15.2 kg/ha. Farm-C (*290 mature cows with 11,340 kg/cow/year milk production level and 184 ha of farm land*) had a predicted annual P imbalance of 18.7 kg/ha.

Farm-A, the organic-certified farm, had the lowest P imbalance per area and per cow compared to the other two study farms mainly because it has minimized its P inputs by producing most of its herd's feed on the farm. As described previously, this organic farm produces an adequate amount of high-quality forage on the farm, uses an intensive grazing system, and does not import any fertilizer and protein feed supplements. This farm currently imports only organic energy supplements from off-farm sources,

Table 4
Integrated Farm System Model (IFSM)-predicted phosphorus imported, exported, and balances for the study farms under the current (baseline) farming system.

	Farms		
	Farm-A	Farm-B	Farm-C
	75cows/89 ha	135cows/146 ha	290cows/184 ha
P imported, kg/ha	13.3 (SD = 0.9)	28.2 (SD = 0.4)	41.7 (SD = 1.4)
Feed	12.7	21.2	40.7
Fertilizer	0.0	6.7	0.2
Precipitation	0.7	0.2	0.8
P exported, kg/ha	7.8 (SD = 1.0)	13 (SD = 2.0)	23.0 (SD = 0)
Milk and animal	7.8	8.3	19.5
Feed	0.0	4.7	0.0
Manure	0.0	0.0	3.5
P balance[a], kg/ha	5.5(SD = 1.0)	15.2(SD = 2.0)	18.7(SD = 1.4)
Imported P remaining on farm, %	41	56	45

P = phosphorus.
[a] P balance = P imported – P exported.

and most energy supplements have lower P content compared to protein supplements. Though the farm has lowest milk production level per cow, it has maintained sustainability by producing a high-priced organic certified milk on a well-managed pasture-based farm system. Because this farm does not import any P fertilizer, the critical source for the relatively small P imbalance on farm can be attributed to the slightly higher levels of dietary P in the supplemental mineral P and vitamin mix fed (0.41% P of DM ration vs. the NRC-recommended 0.38% P of DM ration).

On the other hand, Farm-B, the fully confined farm, had higher P imbalance per area and per cow compared to Farm-A because the farm exports of this farm accounted for less of the P that came into the farm (in feeds and fertilizers) than Farm-A. In addition to the corn silage used by its herds, this farm currently produces extra corn silage for sale to generate income secondary to the sale of milk. Hence, the farming system of this farm can be considered as a mixed farming system because it integrates both animal and crop productions. Based on the model predictions, about 54% of the total farm P imported (in fertilizer and feed) remains on the farm (Table 4). In other words, the amount of P imported to the farm as supplemental feeds and fertilizer is roughly twice the amount of P exported off the farm in milk and animal products and corn silage sold. The amount of P imported as starter P fertilizer alone accounts for 24% of total farm P imports (calculated from Table 4). Thus, the critical sources for the P imbalance of the farm may be attributed to the higher dietary P levels, imported supplemental feeds, fertilizer used, and under-utilized farm area for forage production. As previously mentioned, on average, only about 58% of the farm area (calculated from Table 2) is managed each year for forage production mainly due to logistical limitations (resources, time, and labor). The unutilized area could be used either to produce more forage on the farm or for grazing purpose, so that more feed could come from homegrown feeds, decreasing the amount of purchased feed required and farm P imports. Farm milk production per cow may not be considered optimum compared to the milk production potential of cows of the same size, but the farm currently generates income secondary to the sale of milk by selling the extra corn silage produced on the farm.

Finally, Farm-C had almost all P inputs as feed and had a significant P imbalance that needs to be addressed under the existing farm system. Note that this farm has used 100% of its land area for forage production, operated at high milk production levels, and exported 10% of the total manure to other farms in the area. However, about 45% of the imported P still remains on the farm (Table 4). Critical sources of P imbalance for this farm include the high dietary P levels, excessive use of imported supplemental feeds, and shortage of farm area for forage production and manure application.

Farm-C has also high animal density of 3.2 AEU/ha (AUE = animal equivalent unit; 1 AEU equals 454 kg animal live weight). With this high animal density, the manure P of this farm is expected to exceed crop P requirements (Saam et al., 2005). Even by using animal density as a nutrient balance measure, Farm-C has a unique challenge in adequately recycling manure P produced on the farm. In contrast, the animal densities of Farms A and B are 1.5 and 1.3 AEU/ha, respectively, considering all owned farm land. Based on the Saam et al. (2005) categorization, both farms fall into the low animal density category (less than 1.85 AEU/ha) and farms in this category are less likely to have a shortage of cropland area to recycle manure P produced on the farm. The estimation of farm animal density, used as a general indicator of farm nutrient balance in most existing nutrient management plans, can be used as a starting point for assessing the overall nutrient balance for a farm. However, such assessment lacks the detailed accounting of P in farm inputs and outputs. Thus, it may not be adequate in identifying causes of P imbalances, such as the P imbalance identified in Farm-B, which in the long-term may cause an increased soil-P build-up and a potential risk for high P loss. By doing a detailed accounting of P sources on the farms, specific causes of P imbalance can be revealed and appropriate farm strategies needed to address the imbalance problem can be designed.

3.3. Effectiveness of alternative farm management options

In the previous sections, we presented the status of three study farms with respect to their P balances, and identified potential causes for the P imbalance problem that each farm had. The next question then becomes *how to address the P imbalance problems*. Because every farm is unique in terms of its P imbalance problem, farming systems, physical characteristics, mission, economic assets, and personal preferences, the potential solutions and challenges in achieving P imbalance reduction and economic goals also vary. In addition, actual implementation of any management measures aimed at controlling P pollution is ultimately done on a farm-by farm basis. Thus, alternative farm management scenarios analyzed for addressing farm P imbalance problems (Table 1) were designed for each farm by considering the farm's unique characteristics. The following sections discuss the results of our modeling analysis on the P imbalance reduction and economic potentials of alternative farm management strategies for each farm. The management strategies were analyzed based on the following categories: feed production and utilization, P-related environmental impacts, and economic impacts.

Modeling results presented in Tables 5–7 depict predicted values for the baseline scenario and changes from the baseline values for each alternative scenario considered in each study farm. The

Table 5
Integrated Farm System Model (IFSM)-simulated outputs for baseline scenario and changes in simulated outputs from the baseline scenario for alternative management scenarios for Farm-A.

IFSM model output	Baseline[b]	Change in value[a] as compared to the baseline scenario	
		Scenario I	Scenario II
Grass–legume mix, tonnes of DM	284	0	+142
Corn silage, tonnes of DM	58	0	−58
Grazed grass forage, tonnes of DM	140	0	0
Forage sold, tonnes of DM	0	0	0
Energy supplement, tonnes of DM	154	0	+3
Mineral and vitamin mix, tonnes of DM	5	−1	−1
Milk produced, kg/cow/year	7258	0	0
Phosphorus imported, kg/ha	13.3	−3.6	−3.5
Feed	12.7	−3.6	−3.5
Fertilizer	0.0	0.0	0.0
Precipitation	0.7	0.0	0.0
Phosphorus exported, kg/ha	7.8	0.0	0.0
Milk and animal	7.8	0.0	0.0
Feed	0.0	0.0	+0.2
Manure	0.0	0.0	0.0
Phosphorus balance, kg/ha	5.5	−3.6	−3.7
Manure produced, tonnes DM	211	0	+6
Phosphorus in manure, kg	1038	−137	−139
Cost and return expressed per mature cow, $/cow			
Milk and animal income	4365	0	0
Total production cost	2674	−7	−58
Machinery and other operating costs	1366	0	−50
Seed, fertilizer, and chemical cost	44	0	−17
Purchased feed	1265	−7	+9
Farm net return	1691	+7	+58
Standard deviation in net return	156	+3	+1

[a] Change in value = alternative scenario value − baseline scenario value.

[b] Baseline = current farming system; Scenario I = dietary phosphorus reduction to match NRC recommendations; Scenario II = Scenario I + corn land converted to high-quality grass production; DM = dry matter.

Table 6
Integrated Farm System Model (IFSM)-simulated outputs for baseline scenario and changes in simulated outputs from the baseline scenario and for alternative farm management scenarios for Farm-B.

IFSM model output	Baseline[b]	Change in value[a] as compared to the baseline scenario			
		Scenario I	Scenario IIa	Scenario IIb	Scenario IIc
Grass–legume mix, tonnes of DM	193	0	0	+295	+281
Corn silage, tonnes of DM	734	0	−311	−299	−5
Grazed grass forage, tonnes of DM	0	0	0	0	0
Forage sold, tonnes of DM	300	0	−300	−300	−27
Canola seed produced, tonnes of DM	0	0	+56	0	0
Corn meal/citrus supplement, tonnes of DM	164	0	−1	−8	−53
Soy meal supplement, tonnes of DM	163	0	+1	−126	−113
Canola meal supplement, tonnes of DM	64	0	−29	−60	−61
Mineral and vitamin mix, tonnes of DM	9	−4	−4	−1	−1
Milk produced, kg/cow/year	8165	0	0	0	0
Phosphorus imported, kg/ha	28.2	−4.7	−6.1	−14.1	−12.4
Feed	21.2	−4.7	−6.1	−11.3	−12.4
Fertilizer	6.7	0.0	0.0	−2.8	0.0
Precipitation	0.2	0.0	0.0	0.0	0.0
Phosphorus exported, kg/ha	13.0	0.0	−3.6	−3.9	0.0
Milk and animal	8.3	0.0	0.0	0.0	0.0
Feed	4.7	0.0	−3.6	−3.9	0.0
Manure	0.0	0.0	0.0	0.0	0.0
Phosphorus balance, kg/ha	15.2	−4.7	−2.5	−10.2	−12.1
Manure produced, tonnes DM	465	0	+8	+83	+68
Phosphorus in manure, kg	3399	−678	−620	−1041	−1220
Cost and return expressed per mature cow, $/cow					
Milk and animal income	2432	0	0	0	0
Income from forage sale	306	0	−306	−306	0
Total production cost	1893	−17	−48	−192	−195
Machinery and other operating costs	1015	0	+53	+151	+174
Seed, fertilizer, and chemical cost	79	0	−13	+49	+72
Purchased feed	799	−17	−91	−392	−441
Farm net return	845	+17	−255	−114	+195
Standard deviation in net return	130	+3	+17	+25	+12

[a] Change in value = alternative scenario value −baseline scenario value.

[b] Baseline = current farming system; conditions before management changes, dietary phosphorus reduction to match the NRC recommendations; Scenario IIa = Scenario I + grow canola seed to be used as feed source on the proportion of corn area used for silage production for sale under baseline; Scenario IIb = Scenario I + grow high-quality forage (grass–legume mix) on the proportion of corn area used for silage production for sale under baseline; Scenario IIc = Scenario I + keep the baseline corn silage production for sale + grow more high-quality forage (grass–legume mix) on the under utilized area of the farm; P = phosphorus; DM = dry matter.

changes were calculated as the differences in values between the alternative and baseline scenarios such that a negative change represents a reduction, and a positive change represents an increase in the predicted value compared to the baseline condition. Thus, the direction and magnitude of changes in economic or environmental factors resulting from implementation of an alternative scenario are shown. By comparing simulation results for current (baseline) and alternative management strategies, the effectiveness of alternative management strategies in reducing P imbalances were determined. These results are presented in the following sections separately for each farm.

3.3.1. Farm-A

By reducing the dietary mineral P rations to match NRC recommendations (*Scenario I*), the model predicted a 1 tonne decrease in the amount of mineral P and vitamins mix supplements purchased annually. Note that this farm is currently overfeeding P by 8% compared to the highest 0.38% NRC-recommended dietary P level. Reducing imported dietary mineral P, therefore, subsequently reduced the amount of P imbalance by 3.6 kg/ha (Table 5), bringing the farm's net P balance close to zero (considering ± 1 standard deviation of model predictions). This strategy requires minimum strategic change in the farming system and has the potential to help the farm save money on mineral supplements. When dietary P was reduced, the amount of P predicted in excreted manure was also reduced (Table 5), a positive benefit to the environment. When field-applied manure contains lower concentrations of P, off-field P loss will be reduced. This was evidenced by a field-based study by Ebeling et al. (2002) that showed a reduced soluble P loss in runoff from fields that received dairy manure with reduced dietary P level.

Additionally, because Farm-A intends to convert its poor productivity corn fields to produce high-quality forage (grass–legume mix), a land use conversion was also modeled to assess how this change would affect the amount of purchased energy supplements and ultimately the P imports in the feed. Hence a strategy, *Scenario II*, combining dietary P reduction (*Scenario I*) and conversion of areas in corn silage production to high-quality forage production was evaluated using IFSM. By implementing this strategy (*Scenario II*), IFSM predicted a slight increase in the amount of energy supplement purchases (3 tonnes DM; Table 5) in order to offset the reduction in feed energy available in corn silage under the baseline and *Scenario I* conditions (Table 5). However, there was no appreciable change in the farm's P balance due to this land use conversion. This could be due to the small increase in the amount of energy supplement imported. Because the operating costs assumed for producing corn are higher than those for producing grasses, the model also predicted $7/cow increase in the farm's net return using *Scenario II*. Therefore, this analysis is showing that the shift of corn land to high-quality forage production may be pursued with a minimal effect on the farm's P balance while also maintaining farm profitability.

3.3.2. Farm-B

By reducing dietary mineral P to match NRC-recommended values (*Scenario I*), the model-predicted 4 tonnes DM (Table 6) reduc-

Table 7
Integrated Farm System Model (IFSM)-simulated outputs for baseline scenario and changes in simulated outputs from the baseline scenario for alternative management scenarios for Farm-C.

IFSM model output	Baseline[b]	Change in value[a] as compared to the baseline scenario		
		Scenario I	Scenario IIa	Scenario IIb
Grass forage, tonnes of DM	914	0	+308	+308
Corn silage, tonnes of DM	190	0	−190	−190
Grazed grass forage, tonnes of DM	193	0	0	0
Corn silage purchased, tonnes of DM	678	0	−39	−440
Grass forage on rental land, tonnes of DM	–	–	–	+670
Energy supplement, corn meal, tonnes of DM	270	0	−16	−43
Cotton seed supplement, tonnes of DM	130	0	+1	−15
Protein supplement (DDG), tonnes of DM	441	0	−74	−172
Mineral and vitamin mix, tonnes of DM	21	−4	−2	−1
Milk produced, kg/cow/year	11,340	0	0	0
Phosphorus imported, kg/ha	41.7	−3.0	−5.0	−17.5
Feed	40.7	−3.0	−4.8	−17.3
Fertilizer	0.2	0.0	−0.2	−0.2
Precipitation	0.8	0.0	0.0	0.0
Phosphorus exported, kg/ha	23.0	−0.3	−0.2	−0.4
Milk and animal	19.5	0.0	0.0	0.0
Feed	0.0	0.0	0.0	0.0
Manure	3.5	−0.3	−0.2	−0.4
Phosphorus balance, kg/ha	18.7	−2.7	−4.8	−17.0
Manure produced, tonnes DM	927	0	+4	+78
Phosphorus in manure, kg	5684	−484	−453	−614
Cost and return expressed per mature cow, $/cow				
Milk and animal income	4038	0	0	0
Total production cost	3074	−5	−99	−285
Machinery and other operating costs	1875	0	+10	+155
Seed, fertilizer, and chemical cost	112	0	−13	+5
Purchased feed	1087	−5	−96	−446
Farm net return	964	+5	+99	+285
Standard deviation in net return	70	+1	+14	+55

[a] Change in value = alternative scenario value − baseline scenario value.

[b] Baseline = current farming system; Scenario I = dietary phosphorus reduction to match NRC recommendations; Scenario IIa = Scenario I + corn land converted to high-quality forage (grass–legume mix) production; Scenario IIb = Scenario IIa + rent and expand land to grow high-quality forage (grass–legume mix); P = phosphorus; DM = dry matter; DDG = dry distillers grain.

tion in the amounts of P mineral and vitamins mix supplement needed. As a result, the farm's P imbalance was significantly reduced by 31% (Table 6). As previously discussed, reducing the dietary mineral P requires relatively minimal strategic change in the overall farming system and it was considered as a first major step in reducing farm P imbalance for this farm. Implementation of the strategy under *Scenario I* was beneficial in reducing the P imbalance, manure P content, and the costs of feeds. However, Farm-B still had a 10.5 kg/ha P imbalance remaining after implementation of this strategy. Thus, to further reduce the remaining P surplus on the farm, various alternative sources of energy and protein feed supplements were assessed with *Scenarios IIa, IIb, and IIc* (Table 1).

By growing canola seed on a 22 ha area, on part of Farm-B's corn fields currently used to produce extra corn silage for sale, and by setting dietary P levels to match the NRC-recommended values (*Scenario IIa*), IFSM predicted a reduced P importation of 6.1 kg/ha (Table 6) as the on-farm grown canola seed replaced some of the feed protein supplements (mainly canola meal) that the farm is currently purchasing. As a result, the model predicted a reduction in the total P imported to the farm (Table 6). However, since the farm under this scenario no longer sells corn silage, the amount of P exported from the farm was reduced by 3.6 kg/ha (Table 6), resulting in a minimal benefit of this strategy with regard to reducing the overall farm P surplus. With respect to the economic effects of this strategy, despite $91/cow decrease in purchased feeds, the model predicted a reduced farm net-return of $255/cow due to both the $306/cow losses of income from corn silage sale and the $55/cow increases in cost of production needed in canola seed production and processing (such as, crushing canola seed before it is mixed in the ration). The sale of the corn silage is currently benefiting the farm both as a source of income and in increasing the P exported from the farm. A potential risk of growing corn silage may be erosion and its associated P losses from the corn fields. Of note is that this farm has implemented a set of management practices, including contour plowing and strip cropping (of corn and grass), in order to address the potential risks of high erosion and associated P loss from corn fields.

On the other hand, by growing high-quality forage (grass–legume mix) on a 22 ha area (part of corn fields currently used to produce corn silage for sale) and utilizing it as a feed supplement, and by setting the dietary P to match the NRC-recommended values (*Scenario IIb*), the model predicted a dramatic decrease in the amount of supplemental feed, mainly protein (soy and canola meals), purchased annually (186 tonnes DM; Table 6). This strategy required an increase in the amount of forage fed to each cow in order to utilize the 295 tonnes DM increased forage production. Dietary forage levels after implementation of *Scenario IIb* were 75% of the total ration DM for the farm. As a result of utilization of the increased on-farm-produced forage and decreased importation of protein feed the farm's P imports were reduced compared to *Scenario I* and *Scenario IIa* (Table 6). These model results indicate that, for Farm-B, increasing high-quality forage production and utilization (*Scenario IIb*) is preferable to growing canola seed (*Scenario IIa*), as this strategy reduces the amount of protein feed supplement required, total P imports, and costs of purchasing protein supplements. Compared to *Scenario I*, the amount of P excreted in manure was also slightly reduced as the cows were fed more from homegrown-forage feed that more closely matches NRC-recommended levels. However, this strategy may not benefit the farmer economically; the predicted farm net-income under this scenario was lower by $114/cow from the baseline because the farm lost income earned from selling corn silage.

Seeking to maintain the farm's profitability, a more aggressive approach was also assessed. This approach, *Scenario IIc*, combined the current system, which still allowed the farm to produce corn silage for sale, with expansion of forage production on the under-utilized farm area. As previously mentioned, 51 ha (of the farm's 146 ha) are currently used for corn silage production. Of the other 95 ha farm area, only 34 ha is used to grow grass–legume mix forage. In *Scenario IIc*, the area used in grass production was doubled to produce high-quality forage. In addition, the cows were fed with a high-forage diet (average forage level of 74% of total ration DM) while meeting energy and protein requirements with supplemental feeds and precisely balanced dietary P levels. In practice, careful considerations are needed in formulating diets with high forage as high-forage diets are more likely to limit milk production. By implementing the strategies under *Scenario IIc*, the IFSM-predicted farm P imbalance was dramatically reduced by 10.2 kg/ha (compared to the 15.2 kg/ha baseline P imbalance) and farm profitability was increased by $195/cow. Under this scenario, the predicted farm P imbalance was 3.1 kg/ha (calculated from Table 6). Considering the ±2 kg/ha standard deviation of model predictions for P balance, the farm's net P balance is close to zero under this scenario.

In summary, the model simulation results suggest that major reductions and possibly zero net-P accumulation on the farm and eventually within the soils are achievable if Farm-B combines a reduction in dietary P inputs with increase in on-farm production and utilization of forage. Generally, as long as the costs saved by buying less feed supplements are higher than the costs of increasing forage productivity, the profitability of the farm can be maintained or even increased.

3.3.3. Farm-C

Similar to the previous study farms, the strategy of reducing dietary P to match the NRC-recommended values, *Scenario I*, was implemented as a first step. Recall that, based on detailed feed analysis data gathered from this farm, dairy dietary P was found to contain 0.50% DM of total ration (111 g/day) compared to average 0.38% NRC-recommended dietary P level (91 g/day) for high-producing dairy cows. By implementing a reduction in dietary P while also making sure the energy, protein, vitamins, and mineral requirements of the cows were met, the IFSM predicted that the farm can reduce the amounts of mineral and vitamin mix feed supplement by 20% (calculated from Table 7), P imported to the farm by 20%, and the farm P imbalance from a baseline of 18.7 kg/ha to 16 kg/ha under *Scenario I* (calculated from Table 7). While manure P content and the cost of mineral P supplements were reduced (Table 7), a P imbalance still remained with *Scenario I*.

Further, under *Scenario IIa*, when poor-quality and low-yielding corn silage production was phased out and replaced by high-quality grass–legume mix forage production, in addition to reducing dietary P, the model predicted a remaining P imbalance of 14 kg/ha (Table 7). Hence, *Scenario IIb* was designed to assess ways of addressing the surplus P that still remained on the farm. *Scenario IIb* employed the strategies included in *Scenario IIa* as well as expansion of the land area used in production of high-quality forage by renting extra land. By performing iterative IFSM runs with various quantities of additional rental land, we found that an 81 ha area of rental land would be needed in order to produce adequate high-quality forage feed supplement (670 tonnes DM; Table 6) and to bring the farm P imbalance close to zero (1.7 kg/ha; calculated from Table 7). Under this scenario, *Scenario IIb*, cows were fed with an increased level of forage in their diet (forage level of 63% of total ration DM; results not shown) compared to the baseline scenario (forage level of 55% of total ration DM; Table 3). Consequently, the farm was able to balance the amounts of P imports and exports and increase the annual farm net-return under this scenario. For Farm-C, with limited land resources, renting extra land may be an option in order to produce more on-farm grown feed and reduce P inputs, and to secure more land for manure application. In this scenario, we assumed that rental land was available near this farm from retiring farmers, farmers with additional land, and non-farming landowners. If rental lands are unavailable, the farm may have to rely on exporting manure to off-farm users in order to manage the animal waste and reduce the excess farm P without having to reduce the animal density on the farm. Based on iterative IFSM runs, about 50% of the manure produced on the farm needs to be exported in order for the farm to balanced P inputs and outputs without implementing any additional change from the baseline farm systems. That is, to balance P inputs and outputs by only exporting manure, the farm needs to export another 40% of its manure, in addition to the 10% currently being exported. If exporting manure to off-farm users is not feasible, alternative options of managing excess manure on the farm, such as manure composting, might also be explored.

In summary, compared to Farm-A and Farm-B, Farm-C has limited options for changing its management to mitigate its P imbalance. This is due to the shortage of available land for forage production and manure spreading. In addition to implementing the strategy of reduced and balanced dietary P, a more drastic change in farm management may be needed to reduce P surplus on this farm. Examples of these strategies are: (1) renting extra land for forage feed production so as to reduce supplementary P inputs from feed and to reduce animal density while securing more land for manure application and recycling P, and (2) increasing the amount of manure exported off the farm. If feasible, these strategies could also be combined to mitigate the farm's P imbalance problem.

4. Summary and conclusions

Understanding the root causes of potential P soil build-up on farms can help illustrate the adjustments to farm management strategies that will ultimately reduce P loadings to streams flowing to Lake Champlain. In this study, an accounting of farm P imports (in purchased animal feed and fertilizers) and P exports (in milk, meat, or off-farm sales of harvested crops or other products) was done as a means of determining potential P build-up in farm soils. Identification of farm P imbalances (surplus) is a key step in controlling P loss and it is expected to augment the State of Vermont's efforts at identifying watershed-based critical source areas of P loss from the landscape. Identification of root causes of P imbalance is also expected to help in targeting management solutions to the long-term quality and health of Lake Champlain.

In this study, the Integrated Farm Systems Model (IFSM) was used as a tool in assessing the P balances of three Vermont dairy farms with different farming practices and in exploring the potential for alternative farm management solutions to reduce P surpluses while maintaining farm profitability. All three farms studied were found to have P imbalances, ranging from 5.5 kg/ha to 18.7 kg/ha across the farms. The modeling results illustrate the magnitude of the P imbalance for each farm and identify factors that are likely contributors to the problem. Sources of P imbalances were different for each study farm, emphasizing the benefit of a detailed, farm-by-farm based assessment of P inputs and outputs. Overfeeding of mineral P supplements, under utilization of farm land coupled with lower use of homegrown feed in animal diets, reliance on purchased protein and energy feed supplements to meet animal requirements for growth and production, and high animal density with insufficient farm land area for forage production and for manure application were all contributors to the P imbalances on these farms.

In all three farms, precisely balancing dietary P in animal production was found to help reduce amounts of imported P, and accordingly, P surpluses on the farms. This strategy requires minimal changes to the farming system and has the potential to save money with a positive benefit to the environment. This strategy should, therefore, be promoted as a primary step in reducing P imbalance problems for farms with excess dietary P feeding levels. In addition, on farms with available land area for expanding production of on-farm grown feeds, major reductions and possibly zero net-P accumulation on the farm was achievable while maintaining farm profitability. This was modeled by combining the strategy of increased productivity of on-farm forage production and utilization with a precisely balanced dietary P. On the other hand, for a farm with high animal density and shortage of land area, a drastic change in farm management, including renting extra land and increasing forage feed production on it, and exporting manure produced on the farm may be needed to reduce imports of feed supplements containing P, secure more land for manure application and recycling P, and increase the amount of nutrients consumed on site. Overall, the alternative farm strategies being assessed for each farm address the breadth of root causes of P surpluses on dairy farms. Modeling results demonstrated that by implementing alternative management strategies pertinent to each farm, farm P imbalance problems could be addressed while maintaining farm profitability. The findings presented in this paper may be also used as a general guide in planning for sustainable farming in similar settings. While this study focused on only three farms, this model-based approach employed is widely applicable, as is the methodology of representing existing and alternative whole-farm system management strategies to evaluate and quantify the impacts on farm-level P flows and farm profitability.

When limitations of resources and data make it infeasible to carry out an extensive accounting of P, as was done using the model-based approach used in this study, simply monitoring farms for P inputs and outputs might indicate the overall P balances of farms. Then, for farms with P imbalance problems, appropriate and relevant farm strategies that could address the imbalance problem can be developed by focusing on the potential critical P sources identified in this study. Incorporation of a P accounting method into the existing nutrient management planning effort, such as the Vermont's Natural Resources Conservation Service (NRCS) 590 nutrient management planning, may be beneficial in the future to address and target farm P imbalances and potential P build-up on farm soils. By implementing strategies that balance farm P inputs and outputs, the amount of manure P that must be managed can be reduced and the potential accumulation of P in soils and transport to downstream waterways can be prevented.

Acknowledgments

This research was funded by the Environmental Protection Agency through the Lake Champlain Basin Program and the Vermont Agency of Natural Resources, Clean and Clear Program. The authors would like to thank Dr. Heather Darby, University of Vermont Extension, for providing the detailed farm data needed for this study and for suggesting farm management strategies in use in Vermont. The authors also would like to thank Russell Ford for his tireless effort in gathering and compiling the large amounts of farm record data that were needed for modeling the study farms, and Stephanie E. Hurley for kindly proofreading the draft of this manuscript.

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