WHOLE FARM NUTRIENT BUDGETS OF TWO DAIRY FARMS IN ATLANTIC CANADA

by

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ABSTRACT

Whole farm nutrient budgets (WFNB) enable producers to link dairy herd management with traditional field nutrient management plans. The objective of this study was to calculate WFNBs of nitrogen, phosphorus, and potassium (N, P, and K) at a commercial farm in New Brunswick and in Prince Edward Island. Reliable estimates of N fixation from alfalfa and red clover on the farms were obtained with adjustments to the Høgh-Jensen et al. (2004) dry matter conversion models. The farms had surpluses of N, P, and K. Both farms imported feed as well as nutrient inputs for crop production. Surpluses of all nutrients were typical in comparison to WFNBs of similar dairy farms; however, the nutrient use efficiencies were low. The imported manure and fertilizer used in the crop production components contributed to surpluses of N and P which could likely be reduced to improve overall farm nutrient use efficiency.

LIST OF ABBREVIATIONS AND SYMBOLS USED

%Ndfa : Percent of nitrogen derived from atmosphere

δ^{15}N : ^{15}Nitrogen natural abundance

APASCC : Atlantic Provinces Agricultural Services Coordinating Committee

APC : Animal production component

AU : Animal unit

BNF : Biological nitrogen fixation

CoE: Coefficient of efficiency

CPC : Crop production component

DM : Dry matter

g : gram

Ha : hectare

IoA: Index of agreement

K : Potassium

kg : Kilogram

Mg : Megagram

N : Nitrogen

NRC: National Research Council (United States National Academies)

NSAC : Nova Scotia Agricultural College

NUE : Nutrient use efficiency

P : Phosphorus

SE : Standard error

TMR : Total mixed ration

WFNB : Whole farm nutrient budget

yr : Year

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CHAPTER 1 INTRODUCTION

The trend in modern agriculture has been to increasingly unlink our crop and animal production systems. Agricultural systems which once relied on on-site recycling of nutrients to produce crops and livestock have been separated into specialized operations, often concentrated in different geographic areas. Dairy farms in many regions have followed this trend; however, they remain one of the few modern production systems where both crop and animal production are often carried out on the same farm. Particularly in Atlantic Canada, forage production remains a central component of most dairy operations.

Specialization and intensification have achieved gains in farm productivity, however not without external costs to the environment (Oomen et al., 1998). Like other livestock systems, recent increases in dairy productivity have been attained primarily through intensification on an existing or shrinking land base. As the dairy industry in Atlantic Canada moves towards larger herd sizes and high per cow productivity, farmers are faced with the significant challenge of reconciling profitability and environmental stewardship. Imports of feed and fertilizer that have supported more intense farming practices have been associated with nutrient surpluses on many dairies (Klausner et al., 1998; Anderson and Magdoff, 2000; Powell et al., 2001). Dairy farms with nutrient surpluses can cause or worsen environmental problems including the gradual accumulation of phosphorus (P) in the soil (Hutson et al., 1998; Anderson and Magdoff, 2000; Powell et al., 2001), leaching of nitratre to groundwater (Berry et al., 1993; Hutson et al., 1998) and nitrogen (N) loss to the atmosphere from volatilization of manure ammonium (Hutson et al., 1998; Rotz et al., 1999).

In addition to the gains in productivity farmers have seen through specialization, the specialized focus of research through to extension, and professionals in either crop or animal production, has gradually encouraged separate management of farm components. Nutrient management planning has been exclusive to crop production, while animal production and dairy nutrition has focused on the efficient conversion of feed to milk or meat. Farmers obtain advice and services for these components of their operations through different channels. However, the animal and crop production components of dairy farms are linked and nutrients move between them whether it is accounted for in management plans or not. An effective way to identify nutrient problems which have arisen through intensification is to integrate the management of the crop and livestock components on dairies into one cohesive approach (Rotz et al., 2006).

1.1 WHOLE FARM NUTRIENT BUDGETS

Whole farm nutrient budgets (WFNB) are management tools that allow farmers to assess how their management affects the farm nutrient status (Gourley et al., 2007). In the European Union, fifty different initiatives and programs which account for farm nutrient inputs and outputs have been initiated by advisory services and regulatory agencies (Goodlass et al., 2003). New Zealand has also shifted its nutrient management strategies for dairies to a WFNB approach (Ledgard et al., 2004). Before any broad scale adoption of whole farm nutrient budgets can be expected by governments and farmers in Atlantic Canada, research supporting the value of whole farm nutrient budgets as a management tool in Canada and providing baseline nutrient balance values for nutrient budgets at a regional level is required.

The most common approaches to WFNBs are farmgate and system budgets (Watson et al., 2002). Surveys of farming practices in a region or of a specific farm type typically use farmgate budgets, which evaluate the balance of nutrients leaving and entering the farm (Oenema et al., 2003). System WFNBs include nutrients which leave or enter the farm as well as the flow of nutrients amongst the components of the farm (Watson et al., 2002). For a system WFNB, a dairy farm could be divided into crop and animal production components or further divided into livestock, manure storages, soils, and crops. Combining farmgate budgets and the internal flow of nutrients (a system WFNB) provides a powerful approach to study efficiency of nutrient use (Wattiaux et al., 2005). A systems approach allows for the identification of critical control points for nutrient flows and nutrient use efficiency (Dou et al., 1998). The flow of nutrients in WFNBs can be described using measures of the efficiency in producing managed nutrient outputs, such as crops, milk, animals, or manure. Nutrient use efficiency (NUE) of N is calculated as the quantity of N in managed outputs from the farm (or farm component) as a percentage of the N in total inputs to the farm (or farm component).

Farmgate budgets have revealed several characteristics of nutrient balances common to dairy farms in various regions. Dairy farms commonly run a surplus of N (Rotz et al., 1999) and P (Anderson and Magdoff, 2000; Powell et al., 2001). Purchased feed and mineral supplements are the largest contributors to dairy farm P inputs (Anderson and Magdoff, 2000; Powell et al., 2001; Spears et al., 2003b), while feed and often biological N fixation (BNF) are the largest contributors to dairy N inputs (Spears et al., 2003a; Wattiaux et al., 2005). There have been fewer WFNB studies investigating potassium (K); however, Berry et al. (2003) found K surpluses on organic livestock operations when feed concentrates from off-farm sources were fed to the animals. In comparison, Weller and Bowling (2004) found K deficits among organic farms which used no feed inputs.

System WFNBs on dairy farms studied by Bacon et al. (1990), Paul and Beauchamp (1995), and Lynch et al. (2003) identified the same nutrient surpluses found by farmgate budgets, but they also provide specific information on nutrient cycling within the farms. With respect to nitrogen, Lynch et al. (2003) and Paul and Beauchamp (1995) identified the proportion of crop production component (CPC) nitrogen inputs supplied by biological nitrogen fixation as an important factor affecting NUE of the CPC and the farm as a whole.

1.2 NITROGEN FIXATION AS A NUTRIENT INPUT

Forage crops, often consisting of grass/legume mixtures, are a major component of dairy farms in Atlantic Canada. Rhizobia living in symbiosis with legumes can perform BNF, providing an important source of plant available N to the crop. Biological nitrogen fixation can alleviate the need for inputs of chemical N fertilizers (Ledgard and Steele, 1992). Additionally, the conversion of N to feed is more efficient with legumes as an N source than with applied inorganic N: the N from BNF is less likely to be lost to leaching or volatilization as it is placed in closer proximity to roots (Kohn et al., 1997). Biological nitrogen fixation can represent a significant portion of the N inputs on forage based dairy farms; however, these inputs are very hard to quantify (Gourley et al., 2007; Wattiaux et al., 2005; Lynch et al. 2003).

As previously noted, BNF provides an important contribution to dairy farm N inputs and is a good alternative to expensive inorganic N fertilizers. WFNBs present an opportunity to examine the relative importance of BNF within the overall farm system. However, the current methods for measuring BNF in the field are difficult and expensive (Gourley et al., 2007). Berry et al. (2003) and Ross et al. (2008) both found BNF to be the largest source of uncertainty in N budgets for low input organic farms in the UK, and perennial legume/grass forage systems in Alberta, respectively. Calculation of an accurate WFNB requires good accuracy of nutrient inputs and outputs (Oenema et al., 2003), particularly for inputs or outputs with high values such as BNF. As a result, N fixation is one of the largest sources of error in nutrient budgets when legumes are included in the cropping system (Watson et al., 2002). The WFNB approach accounts for the effect that each component of the farm has on nutrient cycling, and has the potential to identify areas of dairy farm nutrient management which could be improved. However, without an effective means of assessing BNF, a major contributor to dairy farm inputs in Atlantic Canada, the accuracy of WFNBs remains uncertain.

CHAPTER 2 ASSESSMENT OF BIOLOGICAL NITROGEN FIXATION ON NB AND PEI DAIRY FARMS

2.1 INTRODUCTION

Perennial forages on dairy farms in Atlantic Canada often contain mixtures of a legume and non-legume species. The legumes included in forage depend on the climate and soil suitability to each species, as well as the end use of the forage, e.g. hay, silage or for grazing. The most prevalent forage legume species planted in regional mixtures include red clover (*Trifolium pratense*), white clover (*Trifolium repens*), and alfalfa (*Medicago sativa*). Biological nitrogen fixation (BNF) performed by Rhizobium bacteria living in symbiosis with the forage legumes provide an important source of nitrogen (N) for forage production. On a whole farm basis BNF often represents a significant portion of the total nitrogen inputs (Gourley et al., 2007; Wattiaux et al., 2005; Lynch et al. 2003). Calculation of an accurate whole farm nutrient budget requires accurate accounting of nutrient inputs and outputs (Oenema et al., 2003), particularly for inputs or outputs with high values such as BNF. As a result, N fixation is one of the largest sources of error in nutrient budgets (Watson et al., 2002). A convenient and accurate estimate for quantifying N inputs derived from BNF is needed (Watson and Goss, 1997).

2.1.1 Measurements of BNF

In Atlantic Canada it is estimated that 19.5×10^3 t of N are fixed through BNF each year, representing 29% of the N inputs to agricultural crops (Chambers, 2001). However, actual amounts of N fixed and incorporated into crop biomass through BNF are very difficult to directly quantify. Legumes themselves acquire N from the soil at a lower energy cost than through BNF (Vitousek et al., 2002); therefore their plant biomass contains a mixture of N derived from soil and N derived from the atmosphere.

The amount of N derived through BNF is not solely dependent on the genetics of the legume and Rhizobia species. Legume growth, the soil N environment, N fertilization, and competition from grass species are the most prominent factors that influence BNF in pastures (Ledgard and Steele, 1992). The dynamic nature of the factors that influence BNF make accurate measurement of BNF very difficult.

Some of the established methods for assessing BNF include the total N uptake difference method and acetylene reduction assays. Briefly, the total N difference method compares total N in a crop with that of a non-leguminous reference species. The difference in total N offtake of the legume and reference is assumed to be N derived from the atmosphere (Unkovich and Pate, 2000). Acetylene reduction assays have been used extensively in the past; however, they measure the activity of the nitrogenase enzyme. Nitrogenase activity is linked to how much N is fixed; however, it is not a direct measure of actual amounts of N fixed over time.

Isotopic methods are currently favoured for measuring BNF (Herridge et al., 2008). Isotopic methods exploit the difference in concentrations of ^{14}N and ^{15}N isotopes in the atmosphere and in the soil. The atmosphere has a ^{15}N concentration of 0.3663 atom % which is assumed to be constant (Evans, 2001). However, the ratio of ^{14}N and ^{15}N isotopes varies across different N pools in the biosphere due to fractionation of the isotopes. Heavier isotopes require more activation energy in reactions; therefore, soil N transformations such as volatilization, nitrification, and denitrification gradually fraction off the lighter isotope and result in increased abundance of ^{15}N in the soil (Högberg, 1997). Other organic materials which have lost NH_3 such as manure or compost also have greater abundances of ^{15}N in comparison to the atmospheric standard (Högberg, 1997; Lynch et al., 2006). The ratio of ^{14}N and ^{15}N isotopes found in plant tissues relates to the isotopic signature of the plant's N sources (Högberg, 1997). A process like BNF, which draws upon atmospheric N, dilutes the ^{15}N concentration in the plant tissues with respect to the soil ^{15}N concentration.

The two main types of isotopic methods used to measure BNF are the ^{15}N natural abundance (often expressed as δ^{15}N) method and the ^{15}N isotope dilution method (Goh, 2007). The δ^{15}N method utilizes the natural differences between the δ^{15}N in soil N and atmospheric N to estimate the proportion of N in a legume's plant tissues which is derived from the atmosphere. Non N_2 fixing plants are used as a reference for the $\delta^{15}N$ of the soil. By using a reference plant which is growing in close proximity to the legume, the $\delta^{15}N$ of the plant actually integrates the $\delta^{15}N$ of plant available N over the growing period (Shearer and Kohl, 1986). The ^{15}N isotope dilution method artificially labels the soil available N pool with the use of ^{15}N enriched fertilizer. The proportion of N derived from the atmosphere in a legume may then estimated by comparing the atom % excess of ^{15}N, relative to the atmospheric constant, of the legume with that of a non N_2 fixing reference plant. With the addition of ^{15}N enriched fertilizer to the soil N pool, the dilution of ^{15}N isotopes from atmospherically derived N in legume tissues is easier to detect when compared with reference plants which draw only upon soil N (Høgh-Jensen and Schjoerring, 1994). In contrast, the $\delta^{15}N$ method relies on detecting the natural difference between the $\delta^{15}N$ of legumes and associated reference plants which is typically less than 0.0037 atom % ^{15}N excess (Shearer and Kohl, 1986). The $\delta^{15}N$ method therefore requires much more precise analysis of plant samples than the ^{15}N isotope dilution method (Høgh-Jensen and Schjoerring, 1994). Error may also be introduced in the $\delta^{15}N$ method if the difference between $\delta^{15}N$ of legumes and reference plants is less than the natural heterogeneity of the reference plant $\delta^{15}N$ (Shearer and Kohl, 1986).

Despite the limitations to the $\delta^{15}N$ method it has been found to be as accurate as ^{15}N isotope dilution for determining BNF in mixtures of white clover, red clover and grasses (Høgh-Jensen and Schjoerring, 1994). Additionally, the main advantage of the natural abundance method is that it does not require the use of expensive ^{15}N enriched fertilizers making it better suited to field or landscape and commercial farm studies (Unkovich and Pate, 2000). Bowman et al. (2004) and Unkovich et al. (1994) used the $\delta^{15}N$ method for quantifying BNF rates in mixed legume forages across a large number of commercial farms in Australia.

Both ^{15}N isotope dilution and $\delta^{15}N$ methods require a non-N_2 fixing reference plant for the determination of isotopic signature of N derived from the soil. The isotopic signature of the legume is compared with that of the reference plant in order to determine the proportion of N that has been derived from N fixation. When reference plants grown in mixture with legumes are used, these methods can be insensitive to the bi-directional transfer of N between legumes and associated grasses (Høgh-Jensen and Schjoerring, 2000). The choice of appropriate reference species and N transfer between legumes and the reference plants are the largest concerns with the $\delta^{15}N$ method (Carlsson et al., 2009).

2.1.2 Transfer of Fixed N

The transfer of N from legumes to associated grasses is a result of competition for N released from rhizodeposition, and possibly direct transfer through a common mycorrhiza mycelium (Høgh-Jensen 2006). Significant above-ground transfers also occur as grazing animals recycle fixed N from legumes to the soil (Ledgard, 1991). In some cases, up to 50% of grass N needs can be met by transfer from associated clovers (Ledgard, 1991; Soussana and Hartwig, 1997). In alfalfa and grass stands, the ^{15}N dilution method has shown that the proportion of grass N obtained through transfer can range from 26-46% depending on the age of the stand (Burity et al., 1989). Earlier work showed that the transfer of N was not constant throughout a growing season, and the proportion of grass N obtained from alfalfa, red clover or birdsfoot trefoil through transfer ranged from 5-36% (Ta and Faris, 1987). In general, these studies found using the enriched ^{15}N dilution method that the transfer of fixed N from legumes to grasses increases throughout the season from first cut to later cuts (Ta and Faris, 1987; Burity et al., 1989) and from first year to older stands (Burity et al., 1989; Høgh-Jensen and Schjoerring, 2000). However, contrary to these findings, Høgh-Jensen and Schjoerring (1994) found that using the $\delta^{15}N$ method there were not large differences between the isotopic signatures of grass grown in monoculture and grass grown in a mixture of red and white clover.

2.1.3 Choice of Reference Species

In the $\delta^{15}N$ method a non-N fixing reference plant is used to determine the isotopic signature of N derived only from the soil. Soil ^{15}N signatures have considerable spatial variability (Bremer and Van Kessel, 1990), thus affecting the ^{15}N signature of the above ground reference plants used in the in the $\delta^{15}N$ method (Holdensen et al., 2007). Shearer and Kohl (1988) recommended the use of reference plants growing in close proximity to the legumes to account for this spatial variability. Ideally a reference plant should have the same rooting pattern and N uptake characteristics as the legume species; however often these exact qualities are difficult to find in the field. In practice, when sampling mixed legume pastures, Bowman et al. (2003) and Unkovich et al. (1994) separated legumes, grasses, and weeds from each harvest to obtain reference samples specific to each legume analyzed for the $\delta^{15}N$ method. Recent work by Carlsson et al. (2009) has supported the use of several reference species in order to avoid the use of one plant species which may have very different N uptake habits than the target legume.

2.1.4 $\delta^{15}N$ Method in Practice

BNF rates of many leguminous forage crops have been studied extensively in other countries; however there is no data from crops grown in Atlantic Canada. Studies investigating red clover and alfalfa using the $\delta^{15}N$ method, (Table 2.1) have found various ranges of %N derived from the atmosphere (%Ndfa) for these species. There is a notable lack of $\delta^{15}N$ data for alfalfa forages grown in temperate regions. Although the ^{15}N isotope dilution method is more commonly used in studies investigating BNF rates in forages, the $\delta^{15}N$ method has several benefits in an on-farm setting as previously mentioned. However, the $\delta^{15}N$ method tends to result in lower values for %Ndfa in red clover than using the ^{15}N isotope dilution method (Høgh-Jensen and Schjørring, 1994; Huss-Danell and Chaia, 2005; Huss-Danell et al., 2007). Therefore, comparisons of %Ndfa and overall fixed N per area from separate studies may be influenced by the method used in each study. Studies comparing the enriched ^{15}N method and the $\delta^{15}N$

method have not found a consistent difference between reported %Ndfa values; however, they have ranged from near 20% to no statistical difference (Høgh-Jensen and Schjørring, 1994; Huss-Danell and Chaia, 2005; Huss-Danell et al., 2007).

Table 2.1 δ^{15}N ranges of legumes, reference plants, and %Ndfa from BNF studies using the δ^{15}N method

δ^{15}N range of legumes (‰)	δ^{15}N range of reference (‰)	%Ndfa	Location	Study
0.85 to 1.75 (alfalfa)	1.21 to 3.48	45 to 65	Mexico	Crews, 1993
-1.6 to 1.1 (red clover)	-	90	Germany	Carlsson et al., 2009
-1.3 to 3.6 (alfalfa)	1 to 12	72 to 81	Australia	Bowman et al., 2004
-0.9 to -0.2 (red clover)	4.7 to 6.5	68 to 90	Sweden	Huss Danell and Chaia, 2005
-0.45 to 1.4 (red clover)		>80	Sweden	Huss Danell et al., 2007
(red and white clover)	3 to 6.7	55 to 76	Denmark	Høgh-Jensen and Schjoerring, 1994
-0.46 to 1.32 (red clover) 0.06 to 1.22 (alfalfa)	0.07 to 5.49	69	Nova Scotia	Lynch et al., 2010

2.1.5 Estimation of BNF Contribution to Farm N Inputs

Ideally, a practical estimate for BNF on commercial farms should be based on field parameters readily available to farmers such as forage yield, legume content in the sward, and forage protein content. Quantification of N inputs in whole farm nutrient budgets are usually based on some or all of these factors. However, there is no consistently used method for the determination of BNF-N inputs in nutrient budgeting, and often the methods used vary significantly. A study of dairies in Wisconsin assessing different nutrient budgeting programs indicated that BNF could contribute either 24 or 44% of the total N inputs on the same farms, depending on how it was calculated (Towns, 2003 in Wattiaux et al., 2005).

Several models have been proposed to obtain a relatively accurate estimate of BNF. Kristensen et al (1995) created a simple model for estimating BNF based on sward clover content and years since establishment. Other models have been based on dry matter yields of specific legume species (Carlsson and Huss-Danell 2003; Høgh-Jensen et al., 2004). However, none of the available models or data on BNF are derived from research in Atlantic Canada. Choosing a model for BNF estimation without any reference for actual local BNF rates could arbitrarily influence BNF values in whole farm nutrient budgets as noted by Wattiaux et al. (2005).

2.1.6 Objective

The specific objective of this study is to determine if existing models can accurately predict the amount of BNF in mixed legume/grass forage fields on two commercial farms in Atlantic Canada as measured by the ^{15}N natural abundance method.

2.2 MATERIALS AND METHODS

2.2.1 Biological Nitrogen Fixation Measurement with δ^{15}N Method

Two commercial dairy farms were chosen as study sites for investigating WFNB in NB and PEI. The measurement of BNF from forage legumes at these sites served to enhance the accuracy of budgeted N inputs for the WFNB study and also provide valuable data for the assessment of BNF in crops across the Atlantic Canada region. Two fields on each farm were selected for direct measurement of legume BNF. These included grass/alfalfa fields in Perry Settlement NB (Fields 20 and 5678) and grass/alfalfa/red clover fields in Foxley River PEI (Fields DK3 and KK1). Smooth brome (*Bromus inermis*), tall fescue (*Festuca arundinacea*), and timothy (*Phleum pratense*) were the predominant grasses in the forage mixtures at both sites. At each farm site one field in its first year of forage production and another in its second year were chosen (Table 2.2). Cereals undersown with the grass and legume mixture were grown prior to forage on these fields. BNF rates were measured in these fields in 2009 and 2010.

Table 2.2 Management characteristics of NB and PEI fields used in the δ^{15}N study

			NB		PEI	
Field			5678	20	DK3	KK1
Area (ha)			1.5	3.8	8.5	10.5
Years since establishment			1	2	1	2
Manure N inputs[+] (kg N ha^{-1})						
	2009	Summer	104 (52)[◊]	87 (44)	184 (66)	184 (66)
		Fall	95 (48)	125 (63)		
	2010	Spring	84 (42)			
		Summer	100 (54)	97 (53)	193 (45)	
		Fall	123 (64)			
2009 soil test[‡] (mg kg^{-1})		P	79	66	61	45
		K	100	81	81	63
		Ca	1790	3033	881	936
		Mg	112	195	91	98

[‡] Mehlich III soil test
[◊] Values are total N with ammonium N in parentheses
[+] Manure sampled immediately prior to application

In NB, fields 20 and 5678 received manure applications of combined liquid dairy and hog manure. Field 5678 received more manure applications in 2010 than Field 20 (Table 2.2). Soil tests from 2009 indicated there were no major nutrient deficiencies in Field 20 or 5678.

In PEI, Fields DK3 and KK1 received semi-solid dairy manure applications in the summer between first and second cut of 2009. In 2010, only Field DK3 received manure during the summer. Mehlich III soil tests from both PEI fields had medium levels of P and K according to the NB Crop Fertilization Guide (Anonymous, 2001).

Immediately prior to farmers' harvests, fifteen 0.5 m^2 quadrats were sampled along a 'W' shaped transect on each field (Unkovich et al., 1994; Schwenke et al., 1998). The quadrats were spaced to ensure the transect was representative of the entire field. Samples were taken at each cut, June and August in 2009, and early June, July, and September (NB only) in 2010. Although somewhat larger than typical forage sample sizes, Holdensen et al. (2007) found that a 0.5 m^2 quadrat was suitable to ensure reference plant samples could adequately represent the spatial variation of soil ^{15}N signatures. Herbage from each 0.5m^2 quadrat was cut at approximately 3-5 cm stubble height and kept cool until sorting. During the study period, 120 quadrats were harvested from the PEI farm and 150 quadrats were harvested in NB. More samples were obtained from NB because a third cut was taken in the fall of 2010, whereas there were only two cuts in PEI in 2009 and 2010.

Plant material from each quadrat was sorted into legume, grass, and weeds, weighed, then dried (60°C, 48h). Red clover clover and alfalfa were sorted into separate samples. The dried samples were weighed to determine dry matter yield of each material (alfalfa, red clover, grass and weeds) and ground to pass a 1 mm screen using a Wiley Mill. An approximately 3 g subsample was further ground to a fine powder on a roller grinder (Arnold and Schepers, 2004). Encapsulation of 2.0±0.5 mg legume sub samples and 3.0±0.5 mg grass reference sub samples was completed and then samples were sent for isotopic analysis. M. Stocki at the Department of Soil Science Stable Isotope Facilities at the University of Saskatchewan carried out the analysis on a continuous flow isotope ratio mass spectrometer. The analytical error of the mass spectrometer was low; the mean difference between duplicate samples sent for analysis was 0.048‰.

The δ^{15}N in a sample is expressed in ‰ deviations from the atmospheric standard and is calculated as (Evans, 2001):

Equation 2.1: $$\delta^{15}N = \left(\left(\frac{\mathrm{R_{sample}}}{\mathrm{R_{atmosphere}}}\right) - 1\right) * 1000‰$$

Where R = $\left(\frac{^{15}N}{^{14}N}\right)$ and $\mathrm{R_{atmosphere}}$ is 0.0036765.

The ^{15}N:^{14}N isotope ratios were measured on a continuous flow isotope ratio mass spectrometer. The %Ndfa in a sampled legume was calculated as (Huss-Danell and Chaia, 2005):

Equation 2.2: $$\%\mathrm{Ndfa} = \left(\frac{\delta^{15}N_{\mathrm{referenceplant}} - \delta^{15}N_{legume}}{\delta^{15}N_{\mathrm{referenceplant}} - \beta}\right) * 100\%$$

where the non-legume reference plant representing the isotopic signature of plant available soil N was the grass separated from the forage mixture cut from each quadrat (Bowman et al., 2004; Huss-Danell and Chaia, 2005) and β is the δ^{15}N in legumes when grown in a complete absence of soil available N. β is included in the formula to account for any fractionation of N isotopes within the plant or through the fixation process (Carlsson et al., 2006). Values of β for legume species grown in Truro, Nova Scotia, at the Nova Scotia Agricultural College in a greenhouse environment without any soil or applied N were -0.758‰ for red clover and -0.322‰ for alfalfa, (A. Ward, 2010, personal communication).

It is generally recommended with the δ^{15}N method that there be a difference of at least five δ^{15}N units between the β value for the legume and the associated reference species (Högberg, 1997). This benchmark is used to avoid situations where variation from measurement error coupled with the actual variation in the δ^{15}N of samples could overshadow the difference between δ^{15}N of the legume and reference samples. The method used in this study to calculate each %Ndfa utilizes a pair of $\delta^{15}N_{referenceplant}$ and δ^{15}_{legume} values in Equation 2.2 measured from plant samples obtained from the same quadrat. The error associated with variations in the δ^{15}N in a field may therefore be estimated using the standard error of the mean %Ndfa (Shearer and Kohl, 1986).

For each quadrat, the %Ndfa was multiplied by the total N in the above-ground legume biomass (i.e. above-ground dry matter yield x tissue N concentration) to obtain a quantitative estimate of forage legume BNF derived N (kg BNF-N ha^{-1}) per field. Tissue N concentrations were obtained from the mass spectrometer analysis.

The BNF-N estimates from the δ^{15}N method were compared to estimates obtained using an N balance method for estimating BNF that is applied in other WFNBs Lynch et al. (2003). The method assumes that available N will be utilized by the forage, and any additional N present in the forage offtake is derived from BNF. The available N is assumed to be the sum of N inputs from deposition (5 kg ha yr^{-1}) and fifty percent of the applied total N. Fall applications of manure which were applied after forage harvests were not included in as available N. An important distinction is that the balance method is an estimate of total fixed N present in the harvested forage, including both the N transferred to non-legumes and that present in legumes, whereas the $\delta^{15}N$ method estimates only the fixed N in the legume.

To obtain a value for N fixed by the legumes alone which could be compared with estimates from the $\delta^{15}N$ method, two assumptions were incorporated into the N balance method to quantify the fixed N transferred to non-legumes. Studies investigating the transfer of fixed N from legumes to non-legumes in forages have indicated that the upper range of the grass N derived from fixed N transfer is near 50% (Burity et al., 1989; Ledgard, 1991; Soussana and Hartwig, 1997). If we assume that all N being transferred is derived from fixed N and 50% of the non-legume N offtake is attributed to N transfer, the remainder of the total fixed N represents the N derived from fixed N present in the legume.

Two sample t-tests in Minitab®15 were used for comparisons of the %Ndfa, forage legume composition, N tissue concentration, and $\delta^{15}N$ values between fields, provinces and years; an α of 0.05 was used for all tests. The field sampling methodology was conducted as a survey; therefore detailed statistical analyses suitable for a designed experiment were not carried out.

2.2.2 Model Testing

Estimates for forage BNF-N obtained from models were compared with the measured BNF values from our $\delta^{15}N$ analysis of fields at both study sites. Performance measures were used to select a model that provided the best estimate for BNF-N. The coefficient of efficiency (CoE) and index of agreement (IoA), as described in Astatkie (2006), were used to evaluate the predictive capability of each model based on predicted BNF-N values and the actual field data obtained from the $\delta^{15}N$ and N content analysis on each farm. The CoE and IoA are both calculated relative to the average of all the observed values, resulting in values which are independent of scale and unit of measure. The root mean squared error and the mean absolute error of the models were also calculated to relate the results to the field setting.

2.2.2.1 Carlsson (2005) and Høgh-Jensen et al. (2004) models

Based on a review of studies using isotopic and N difference methods to assess BNF, Carlsson and Huss-Danell (2003), proposed simple models for estimating BNF carried out by legumes in mixed legume/grass forages. In all the studies reviewed by Carlsson and Huss-Danell (2003) dry matter yield (DM) was the most influential factor and could be used as the sole input for models to reliably predict BNF rates for alfalfa and red clover. The original models published in 2003 included intercept adjustments which resulted in inflated BNF predictions when little or no legumes are present. Carlsson (2005) recommended removing the intercept adjustments when applying the models on farms, therefore the Carlsson (2005) models were appropriate for this study (Table 2.3).

Høgh-Jensen et al. (2004) developed a slightly different model for estimating BNF based on DM (Equation 2.3):

Equation 2.3: kg N_{fixed} = DM x %N x %Ndfa x (1 + P_{roots} + $P_{transsoil}$ + $P_{transanimal}$ +$P_{immobile}$) where P_{roots} is the fixed N in the root and stubble, $P_{transsoil}$ is the below-ground transfer of fixed legume N located in the grass in mixtures, $P_{transanimal}$ is the above ground transfer (by grazing animals) of fixed legume N located in the grass in mixtures and $P_{immobile}$ is the fixed N immobilized in an organic soil pool, all expressed as a proportion of total fixed shoot N.

For the purpose of testing the model, only the first portion of the model shown in Equation 2.3 will be used, because our measurements of BNF with the $\delta^{15}N$ method only consider above-ground fixed N in the legume, i.e.

Equation 2.4: kg N_{fixed} = DM · %N · %Ndfa

Both the Carlsson (2005) model and the Høgh-Jensen et al. (2004) model are intended to use legume DM as the only input. In contrast with the Carlsson (2005) model which uses the legume DM multiplied by one constant, the Høgh-Jensen et al. (2004) model uses separate parameters for legume N concentration (%N) and the %Ndfa of the legume in the model for converting legume DM to BNF-N. This allows the model to be adjusted, or tailored to fit specific environments when parameters are known. Høgh-Jensen et al. (2004) cite literature values for each parameter for various legume species and settings; however the values are not based on a comprehensive literature review as was the case in the Carlsson (2005) model. An adjusted Høgh-Jensen et al. (2004) model was tested based on the overall means for tissue N concentration and %Ndfa from field sampling.

Table 2.3 Carlsson (2005) and Høgh-Jensen et al. (2004) models for predicting BNF of red clover and alfalfa

	red clover	**alfalfa**
Carlsson (2005)	kg N_{fixed} = DM x 0.026	kg N_{fixed} = DM x 0.021
Høgh-Jensen et al. (2004)‡	kg N_{fixed} = DM x 0.030 x 0.95	kg N_{fixed} = DM x 0.027 x 0.74
Adjusted◊ Høgh-Jensen et al. (2004) ‡	kg N_{fixed} = DM x 0.032 x 0.77	kg N_{fixed} = DM x 0.034 x 0.72

‡in form of Equation 2.4

◊original parameters substituted with mean %Ndfa and %N from all alfalfa or red clover samples

2.3 RESULTS

2.3.1 Agronomic Results

At the NB site, the total DM forage yields ranged from 7.6 – 9.8 Mg ha^{-1} yr^{-1}. With the exception of Field 5678 in 2009, DM yields of cut 1 tended to be larger than the succeeding cuts from fields at the NB site (Table 2.4). The content of alfalfa in the sward tended to increase numerically from one cut to the next. The mean tissue N concentrations of all alfalfa, red clover, and grass samples was 33.9, 32.1, and 21.8 g N kg^{-1} , respectively.

The DM yields of forages containing both red clover and alfalfa at the PEI site ranged from 7.3 – 8.0 Mg ha^{-1} yr^{-1}. DM yields of cut 1 tended to be larger than the succeeding cuts from fields at the PEI site (Table 2.5). The content of alfalfa in the sward at the PEI site also tended to increase numerically from one cut to the next. Red clover was typically more predominant in the sward than alfalfa and, with the exception of field DK3 in 2009, tended to increase from one cut to the next. Tissue N concentrations of alfalfa and red clover were greater than grasses. The concentration of N in grass tissues generally increased with succeeding cuts within any given field and year. At the PEI site the red clover tissue N concentration decreased from first to second cut in both years.

The N off-take of grasses or legumes was mostly influenced by dry matter yields and the prevalence of the legumes or grasses in the sward. Though legumes tended to be more predominant in later cuts, the DM yields tended to be lower in the second and third cuts (table 2.4 and 2.5).

Table 2.4 DM yield, plant composition, plant tissue N concentration, and N off-take of NB farm site forages.

		DM yield (kg ha^{-1})	% of DM yield			Tissue N concentration (g N kg^{-1})		Nitrogen off-take (kg N ha^{-1})	
			Alfalfa	Grass	Weeds	Alfalfa	Grass	Alfalfa	Grass
Field 20	2009								
	cut 1	4350 (230)[z]	18.7 (3.0)	67.0 (3.6)	14.3 (2.2)	33 (0.6)[y]	15 (0.2)	27.3 (4.8)	44.5 (2.8)
	cut 2	3330 (140)	43.9 (4.9)	33.4 (3.6)	22.7 (2.0)	29 (0.6)	20 (0.6)	42.8 (5.0)	21.3 (1.8)
	2010								
	cut 1	4230 (160)	22.6 (5.0)	60.5 (4.6)	16.9 (2.0)	31 (0.8)[y]	17 (0.7)	31.7 (8.1)	41.7 (3.4)
	cut 2	1870 (150)	48.4 (5.0)	21.5 (2.3)	30.1 (3.7)	30 (0.7)	28 (0.5)	30.2 (4.5)	10.6 (1.3)
	cut 3	1480 (130)	50.5 (5.2)	21.6 (2.2)	28.0 (3.6)	33 (0.6)[w]	27 (0.7)	23.8 (5.3)	7.8 (0.7)
Field 5678	2009								
	cut 1	4000 (250)	23.0 (4.5)	59.7 (4.9)	17.3 (2.9)	36 (1.0)[y]	22 (1.0)	32.7 (6.7)	51.3 (5.8)
	cut 2	4210 (180)	41.8 (5.8)	34.1 (3.8)	24.1 (3.7)	32 (0.5)	24 (1.5)	56.7 (8.4)	31.3 (3.1)
	2010								
	cut 1	4520 (190)	37.3 (6.1)	50.6 (4.9)	12.2 (2.3)	39 (0.9)	26 (1.1)	69.8 (12)	57.5 (5.7)
	cut 2	3300 (200)	56.1 (6.9)	37.8 (6.9)	6.1 (1.2)	33 (0.6)	28 (0.9)[x]	61.0 (8.5)	29.4 (5.8)
	cut 3	1930 (120)	63.7 (4.1)	32.1 (3.9)	4.1 (0.9)	37 (0.6)	36 (0.9)	46.1 (5.6)	21.7 (2.7)

[z] value in parentheses is 1 SE, n=15

[y] n=14, [x] n=13, [w] n=12

Table 2.5 DM yield, plant composition, plant tissue N concentration, and N off-take of PEI farm site forages

		DM yield (kg ha^{-1})	% of DM yield				Tissue N concentration (g N kg^{-1})			Nitrogen off-take (kg N ha^{-1})		
			Alfalfa	Clover	Grass	Weeds	Alfalfa	Clover	Grass	Alfalfa	Clover	Grass
Field DK3	2009											
	cut 1	4440 (230)[z]	5.8 (1.2)	59.5 (3.4)	32.3 (3.3)	2.4 (0.6)	33 (1.0)[x]	31 (0.6)	16 (0.6)	7.9 (1.3)	80.1 (6.3)	22.1 (2.7)
	cut 2	3270 (140)	12.9 (2.8)	54.6 (5.0)	26.5 (3.7)	6.0 (1.4)	38 (1.2)	28 (0.6)	25 (0.9)	17.2 (4.1)	50.5 (5.2)	19.7 (2.2)
	2010											
	cut 1	3880 (130)	8.1 (1.5)	32.2 (4.0)	54.1 (4.0)	5.6 (1.5)	37 (0.9)	36 (0.5)	17 (0.3)	10.4 (2.0)	40.7 (5.2)	30.6 (2.4)
	cut 2	3600 (170)	19.8 (6.3)	52.2 (6.2)	22.6 (3.1)	5.4 (1.2)	29 (0.8)[y]	27 (0.4)	19 (0.5)	19.5 (6.0)	45.0 (5.3)	13.2 (1.6)
Field KK1	2009											
	cut 1	4950 (240)	4.5 (1.4)	12.3 (2.1)	78.3 (3.1)	5.0 (1.1)	39 (1.2)[u]	38 (0.8)	15 (0.2)	6.5 (2.3)	23.2 (4.0)	58.9 (3.1)
	cut 2	3000 (220)	17.6 (3.7)	18.7 (2.9)	56.8 (3.7)	7.0 (1.8)	25 (1.1)[x]	32 (0.8)	19 (0.5)	21.0 (5.0)	17.3 (2.9)	30.9 (1.6)
	2010											
	cut 1	4950 (310)	4.9 (1.1)	3.6 (1.2)	77.8 (3.2)	13.8 (3.3)	40 (1.7)[w]	39 (1.1)[r]	18 (0.5)	8.4 (2.1)	5.1 (1.6)	59.9 (5.6)
	cut 2	2300 (260)	19.6 (4.9)	16.1 (3.5)	49.8 (5.1)	14.6 (1.9)	29 (1.0)[v]	30 (0.7)[s]	21 (0.2)[t]	13.7 (4.8)	8.8 (2.3)	9.8 (3.1)

[z] value in parentheses is 1 SE, n=15

[y] n=14, [x] n=13, [w] n=12, [v] n=11, [u] n=9, [t] n=8, [s] n=7, [r] n=5

2.3.2 Biological Nitrogen Fixation Results

The $\delta^{15}N$ range of alfalfa samples collected from both sites was -1.50 to 5.53‰. The alfalfa $\delta^{15}N$ values tended to be close to zero, or negative (Tables 2.6 and 2.7). Field 5678 in NB had more variation among samples than other fields and alfalfa $\delta^{15}N$ values for that field ranged from -0.62 to 5.53‰. Red clover $\delta^{15}N$ values had a narrower range than alfalfa, -1.25 to 0.33‰, and tended to be negative (Table 2.7).

The $\delta^{15}N$ of the grasses collected from the NB site tended to numerically decline from one cut to the next (Table 2.6 and 2.7), the last cut of field 5678 in 2010 being the exception. There were no consistent trends observed in the $\delta^{15}N$ of reference grasses in PEI. Despite declines in some of the grass $\delta^{15}N$ values, the grass reference samples collected at both sites always had higher $\delta^{15}N$ values than the legumes collected from the same quadrat. The reference species collected in NB tended to have higher $\delta^{15}N$ values than those in PEI.

The original β values obtained from growing red clover and alfalfa in the absence of soil N proved to be higher than some of the $\delta^{15}N$ values of legume samples from the field. 21 quadrats from NB and 55 quadrats from PEI contained alfalfa with $\delta^{15}N$ values lower than the -0.32‰ value for β, and 11 quadrats from PEI contained red clover with $\delta^{15}N$ values lower than the -0.758‰ value for β. $\delta^{15}N$ values lower than the value of β result in %Ndfa rates of over 100%; therefore, the lowest detected $\delta^{15}N$ values at each experimental site were used for β (Eriksen and Høgh-Jensen, 1998; Hansen and Vinther, 2001). The field derived value of β was set at -1.25‰ for red clover, -1.50‰ for alfalfa from PEI, and -0.73‰ for alfalfa from NB. The same β values were used for both years; Carlsson et al. (2006) indicated that there was little change in β values from year to year in a perennial forage system.

The mean difference between alfalfa β values and the reference grasses was 5.2 and 3.8 $\delta^{15}N$ units in NB and PEI, respectively. The mean difference between the red clover β value and the reference grasses was 3.6 $\delta^{15}N$ units. Although the difference between reference grasses in PEI and the β values was less than five $\delta^{15}N$ units, the standard error of %Ndfa for each harvest and field remained low. The greatest %Ndfa standard error observed in this study was 6% for cuts 2 and 3 in field 5678. Shearer and Kohl (1986) indicate that typical standard error associated with the δ^{15}N method is 5-10 %Ndfa.

Table 2.6 δ^{15}N of legume and grass aboveground biomass and biological N fixation measurements from fields at NB site

		δ^{15}N (‰)		%Ndfa alfalfa	N fixed by alfalfa (kg BNF-N ha^{-1})
		Alfalfa	Grass		
Field 20	2009				
	cut 1	0.0 (0.1)^{z,y}	4.5 (0.2)	86 (1.6) ^{y}	25 (3.9)
	cut 2	-0.2 (0.1)	3.9 (0.1)	89 (1.5)	37 (4.0)
	2010				
	cut 1	-0.1 (0.1)^{y}	4.8 (0.2)	88 (1.6)^{y}	28 (6.5)
	cut 2	0.4 (0.1)	4.2 (0.2)	77 (2.2)	22 (3.0)
	cut 3	0.2 (0.1)^{w}	3.4 (0.1)	76 (3.2 ^{w}	21 (3.2)
Field 5678	2009				
	cut 1	1.7 (0.3)^{y}	6.3 (0.8)	62 (2.9)^{y}	23 (5.0)
	cut 2	0.3 (0.2)	4.3 (0.3)	80 (3.8)	42 (4.7)
	2010				
	cut 1	0.7 (0.2)	5.2 (0.3)	76 (2.6)	50 (8.4)
	cut 2	1.2 (0.2)	3.4 (0.4)^{x}	62 (5.9)^{x}	31 (4.7)
	cut 3	1.2 (0.2)	3.8 (0.3)	57 (5.6)	24 (3.2)

[z] value in parentheses is 1 SE, n=15

[y] n=14, [x] n=13, [w] n=12

The mean %Ndfa of all alfalfa samples collected from the NB and PEI sites was 72%. The alfalfa %Ndfa values from 2009 did not differ significantly from 2010 (p=0.270). However, the mean alfalfa %Ndfa measured in NB, 75%, was significantly greater than that in PEI, 68% (p<0.000). Differences in overall mean %Ndfa between individual fields were marginally significant (p=0.068) in PEI where Field DK3 alfalfa was 66% and Field KK1 alfalfa was 71%. In NB, there was a significant difference (p<0.000) between the overall mean %Ndfa of alfalfa in Field 20 (84%) and Field 5678 (67%). There were some trends in the alfalfa %Ndfa from one cut to the next; however, these trends were not consistent from 2009 to 2010. For example, in NB, %Ndfa alfalfa increased in 2009, while in 2010 it decreased within the season (Table 2.6).

The %Ndfa of red clover sampled in PEI did not differ significantly between fields or years. The mean %Ndfa for red clover from all samples was 77%. In 2009, the %Ndfa from first to second cuts decreased in red clover from field DK3 and increased in red clover from field KK1; however, the same trends were not observed in 2010 (Table 2.7).

Table 2.7 $\delta^{15}N$ of legume and grass aboveground biomass and biological N fixation measurements from fields at PEI site

		$\delta^{15}N$ (‰)			%Ndfa		Fixed N (kg BNF-N ha^{-1})	
		Alfalfa	**Clover**	**Grass**	**Alfalfa**	**Clover**	**Alfalfa**	**Clover**
Field DK3	2009							
	cut 1	0.0 (0.1)[z,x]	-0.6 (0.02)	2.3 (0.2)	62 (2.2)[x]	80 (1.3)	5 (0.8)	64 (5.3)
	cut 2	-0.6 (0.1)	-0.6 (0.04)	2.5 (0.4)	69 (4.0)	75 (1.8)	10 (2.3)	37 (3.4)
	2010							
	cut 1	-0.2 (0.1)	-0.5 (0.05)	2.3 (0.2)	65 (2.5)	77 (2.0)	8 (1.3)	31 (3.9)
	cut 2	-0.4 (0.1)[y]	-0.4 (0.03)	2.0 (0.1)	69 (2.9)[y]	73 (1.3)	14 (4.2)	33 (3.9)
Field KK1	2009							
	cut 1	-0.7 (0.1)[u]	-0.2 (0.1)	2.1 (0.2)	77 (2.4)[u]	68 (1.8)	7 (2.1)	16 (2.8)
	cut 2	-0.2 (0.1)[x]	-0.7 (0.1)	2.1 (0.2)	65 (4.2)[x]	85 (1.6)	16 (3.2)	15 (2.5)
	2010							
	cut 1	-0.6 (0.1)[w]	-0.4 (0.1)[q]	3.3 (0.4)	79 (2.3)[w]	79 (2.2)[q]	7 (1.6)	5 (1.4)
	cut 2	-0.4 (0.1)[v]	-0.4 (0.03)[s]	2.5 (0.1)[t]	70 (3.1)[r]	77 (1.1)[s]	18 (5.6)	9 (2.7)

[z] value in parentheses is 1 SE, n=15

[y] n=14, [x] n=13, [w] n=12, [v] n=11, [u] n=9, [t] n=8, [s] n=7, [r] n=6, [q] n=5

Table 2.8 N fixation estimates of the δ15N and N balance methods for fields at the NB and PEI sites

		Total N off-take of forage (kg N ha^{-1})	**N balance total fixed N [1] (kg BNF-N ha^{-1})**	**N balance fixed N in legumes [2] (kg BNF-N ha^{-1})**	**δ15N fixed N [2] (kg BNF-N ha^{-1})**
Field 20	2009	160	111	67	62
	2010	180	126	79	71
Field 5678	2009	210	103	43	65
	2010	306	209	145	105
Field DK3	2009	293	196	128	116
	2010	216	114	63	86
Field KK1	2009	186	89	30	54
	2010[3]	145	140	89	39

[1] estimate includes total fixed N present in harvested forage (legumes and non-legumes)

[2] estimate includes fixed N present in harvested legume biomass

[3] no N was applied to field KK1 in 2010

The total fixed N estimates derived from the N balance method were greater than those from the δ^{15}N method (Table 2.8). The fixed N estimates for legumes obtained by subtracting fixed N transferred to non-legumes from the N balance total fixed N did not agree with the δ^{15}N method values; however, there was no consistent under or over estimation.

2.3.3 Model Evaluation

Forage sampling in 2009 and 2010 provided 237 test values for alfalfa (142 from NB and 97 from PEI) and 109 values for red clover (all from PEI). The Carlsson (2005) and original Høgh-Jensen et al. (2004) model predictions for alfalfa were very similar; however the Carlsson (2005) model tended to have greater values for the IoA and CoE (Table 2.9). Both alfalfa models had a negative bias tended to underestimate BNF (Figures 2.1 a and b), whereas the red clover models had a positive bias and overestimated BNF (Figures 2.2a and b). The adjusted Høgh-Jensen et al. (2004) model had similar values for the IoA and CoE than the original and the Carlsson (2005) model for both legumes. However, the adjusted Høgh-Jensen et al. (2004) model did not have as strong a bias for under or overestimation of BNF as the other models (Figures 2.1c and 2.2c)

Table 2.9 Performance measures and error of BNF model predictions

Measure	Model	Alfalfa	Red clover
Index of Agreement^{+}	Carlsson (2005)	0.76	0.98
	Høgh-Jensen et al. (2004)	0.74	0.97
	Adjusted Høgh-Jensen et al. (2004)‡	0.74	0.98
Coefficient of Efficiency^{+}	Carlsson (2005)	0.95	0.93
	Høgh-Jensen et al. (2004)	0.94	0.84
	Adjusted Høgh-Jensen et al. (2004)	0.95	0.95
Mean Absolute Error	Carlsson (2005)	4.84	2.82
	Høgh-Jensen et al. (2004)	5.34	5.83
	Adjusted Høgh-Jensen et al. (2004)	4.49	1.19
Root Mean Squared Error	Carlsson (2005)	8.34	6.16
	Høgh-Jensen et al. (2004)	8.71	9.25
	Adjusted Høgh-Jensen et al. (2004)	8.36	4.99

$^{+}$ For both measures, values closest to one are best

‡adjusted %N and %Ndfa parameters

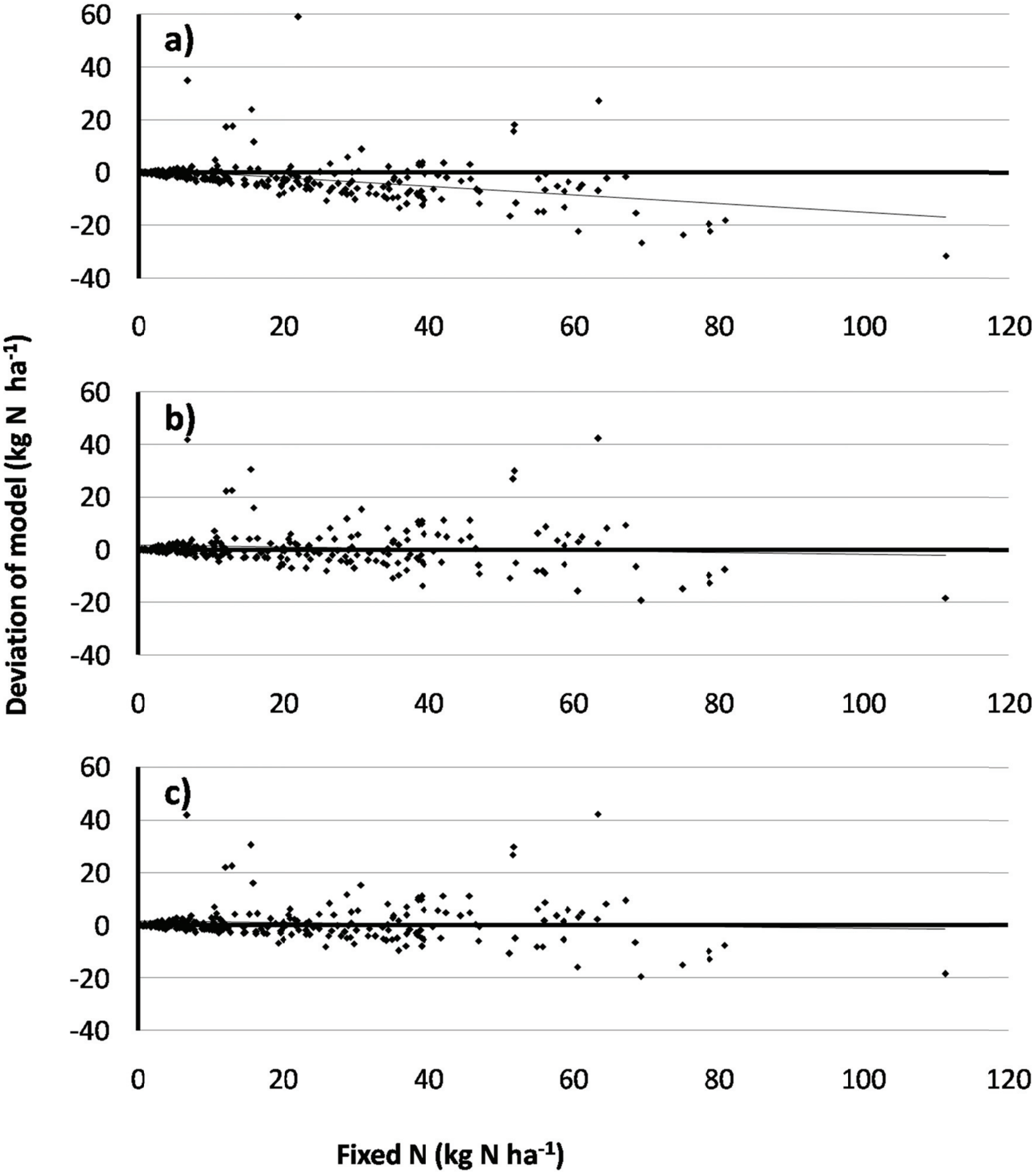

Figure 2.1 Deviation of models from measured fixed N of alfalfa: a) Carlsson (2005) model; b) Høgh-Jensen et al. (2004) model; c) Adjusted Høgh-Jensen et al. (2004) model

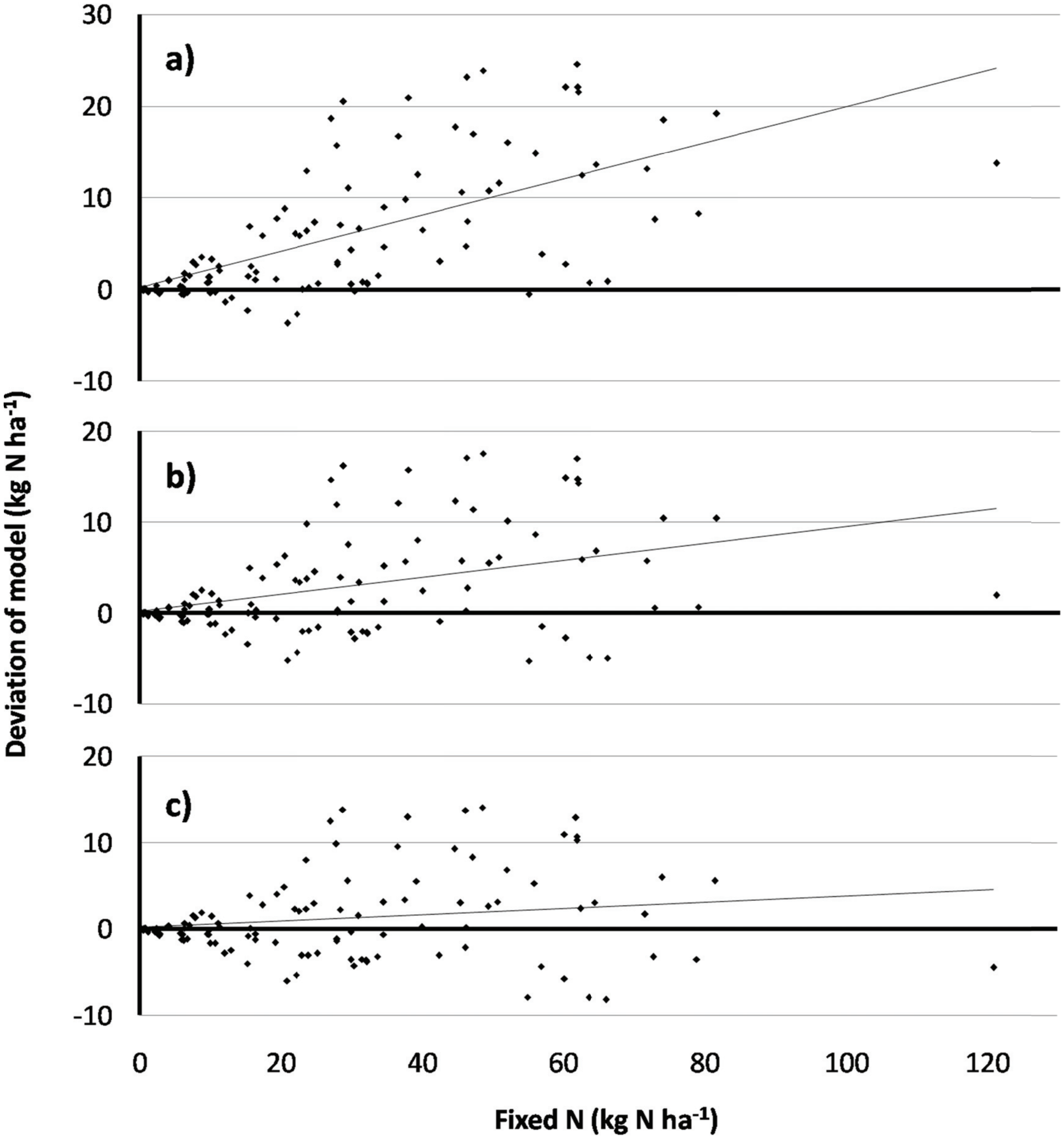

Figure 2.2 Deviation of models from measured fixed N of red clover: a) Carlsson (2005) model; b) Høgh-Jensen et al. (2004) model; c) Adjusted Høgh-Jensen et al. (2004) model

2.4 DISCUSSION

2.4.1 Agronomic Parameters

The measured values of alfalfa DM yield in this study fell within the 6.74 – 9.35 Mg ha^{-1} range of alfalfa yields observed across the Atlantic Canada region by Bélanger et al (1999). Lynch et al. (2004) reported slightly lower total DM yields for red clover/grass forage in Nova Scotia. The DM yields for first cut of red clover/grass forage at the PEI site in this study were similar to those reported by Lynch et al. (2004); however, the yields from the second cut were much greater than those observed by Lynch et al. (2004). Lemieux et al. (1987) reported total DM yields for forage mixtures containing red clover in Quebec that were similar to those found at the PEI site in this study.

Dahlin and Stenberg (2010) also observed the trend of increasing legume contents from one cut to the next in mixed legume crops as found at both sites in this study. All fields in this study were under a relatively high N input regime from applied dairy manure. The predominance of legumes in mixed legume and grass forages is restricted when receiving high N input treatments (Høgh-Jensen and Schjoerring, 1994; Carlsson and Huss-Danell, 2003). However, in 2010, field KK1 received no N inputs from manure and the content of red clover and alfalfa in the forage DM remained low in comparison to the other fields. Similarly, at the NB site in 2010, field 20 received approximately half the manure N inputs that were applied to field 5678 – excluding fall manure applied to 5678 after the third cut harvest. However, the alfalfa contents of the forage DM were higher in field 5678 than in Field 20 in 2010. Carlsson and Huss-Danell (2003) indicate that when applied N levels are in excess of 150 kg N per hectare, clover proportions in the sward are restricted to approximately 50% or less, which is generally consistent with the findings in this study.

Tissue N concentrations of legumes were similar to those observed by Ta and Faris (1987) and Huss-Danell et al. (2007). Ta and Faris (1987) also noted that grass N content increased with each cut in their unfertilized greenhouse experiment and attributed it to the release of N from decomposing legume root and nodule tissues. However, Ta and Faris (1987) found legume N content increased along with that of grasses throughout the season, contrary to the results of this study. In this study, legume tissue N content tended to decline with each subsequent cut. N from decomposing root and nodule tissues would be equally available to legumes and grasses in the sward; however it is often reported that grasses are better at competing for soil N than associated legumes (Huss-Danell et al., 2007; Dahlin and Stenberg, 2010; Ledgard and Steele, 1992). Contrary to this study, and that of Ta and Faris (1987), Huss-Danell et al. (2007) noted in their field experiments with mixed red clover and grass forages that tissue N concentration in grasses declined from first to second cut.

2.4.2 Biological Nitrogen Fixation

The range of alfalfa δ^{15}N from this study, -1.5 to 5.5‰, was similar to the -1.3 to 3.6‰ range reported by Bowman et al. (2004) for alfalfa sampled from various commercial farm sites. Crews (1993) reported a fairly narrow range, and slightly higher alfalfa δ^{15}N values (0.85 to 1.75‰), compared with the current study, however this was from a plot experiment at one location in Mexico. With δ^{15}N values close to zero, Huss-Danell and Chaia (2005), Huss-Danell et al. (2007), and Carlsson et al (2009) measured δ^{15}N values that were similar to this study for red clover.

Høgh-Jensen and Schjoerring (1994) and Huss-Danell and Chaia (2005) observed δ^{15}N values (3 to 6.7‰) for grass references grown in mixtures with forage legumes similar to those seen in NB (2.1 to 12.6‰). The PEI grass δ^{15}N values (-0.1 to 6.2‰) were lower than those in NB, however still comparable to references used by Crews (1993) and Bowman et al. (2003) which ranged from 1 to 12‰. The δ^{15}N method is not able to specifically account for the cycling of N through the forage system (Høgh-Jensen, 2006). However, declines in the δ^{15}N of the grasses throughout the season could be attributed to the grasses obtaining some N that had been fixed by the associated alfalfa through belowground transfer. Using the enriched ^{15}N dilution technique to investigate the transfer of N from alfalfa and red clover to associated grasses, Ta and Faris (1987) noted that amounts of N derived from legume N in grasses increased from one cut to the next. This does support the hypothesis that the observed declines in grass δ^{15}N could be due to increasing amounts of N transfer happening throughout the season. The difference between the δ^{15}N of each paired grass reference and legume sample should also decline throughout the season if N transfer is occurring, and this trend was significant both years in Field 20, and in 2010 in Field 5678 (data not shown). That evidence of N transfer from legumes to associated reference grasses was not uniformly observed at all sites could be attributed to a reduced reliance of grasses on N transfer from legumes in the presence of abundant soil N due to the high N inputs applied to the fields used in this study. N transfer is most important as a source of N for grasses in mixed forages managed with low external nutrient inputs (Heichel and Henjum, 1991; Høgh-Jensen and Schjoerring, 2000).

As noted, the original β values obtained from growing red clover and alfalfa in the absence of soil N were greater than some of the δ^{15}N values of legume samples from the field. This suggests that more isotopic fractionation occurred in the legumes grown in the fields than in the greenhouse experiment. Fractionation during the BNF process is well documented (Hogberg, 1997). Legume δ^{15}N values lower than 0‰ indicate that fractionation during BNF is occurring as the N incorporated in plant tissues is depleted in ^{15}N with respect to the atmospheric constant. Fractionation during BNF is influenced by rhyzobium strains (Carlsson et al., 2006), which could have resulted in the difference between field values measured in NB and PEI and greenhouse derived β values measured in Nova Scotia. The alfalfa and red clover plants grown in the greenhouse for determining β were harvested at the first bloom after seeding, whereas field samples came from established perennial forage fields, a difference which may have influenced the measured legume δ^{15}N values. Accounting for isotopic fractionation within the legume is required to avoid an overestimate of %Ndfa (Carlsson et al., 2006). The %Ndfa values in this study are therefore based on the assumption that the lowest detected δ^{15}N values from the field are from alfalfa and red clover plants relying on 100 %Ndfa.

The β values determined from the lowest detected field δ^{15}N values were similar to values cited in δ^{15}N studies, which typically fall between -1 and -2‰ (Shearer and

Kohl, 1986; Eriksen and Høgh-Jensen, 1998; Carlsson et al. 2006). Legume field samples with δ^{15}N values lower than experimentally derived β values are cited in several δ^{15}N studies (Hansen and Vinther, 2001; Høgh-Jensen and Schjoerring, 2004; Carlsson et al. 2006; Carlsson et al. 2009). Eriksen and Høgh-Jensen (1998) found close agreement between their experimentally derived β value for white clover, -1.4‰, and the lowest δ^{15}N values found in field samples.

The %Ndfa values for alfalfa found at the NB and PEI sites fall within the ranges measured using the ^{15}N isotope dilution technique on alfalfa grown in mixed swards with grasses in other Canadian provinces. Burity et al (1989) found 62-83 %Ndfa and Walley et al. (1996) found 74-89 %Ndfa in Ontario and Saskatchewan, respectively. Similar %Ndfa values, 70-80%, were reported for alfalfa grown in mixed forages in Minnesota (Heichel and Henjum, 1991) and southern Sweden (Wivstad et al., 1987). %Ndfa values for alfalfa obtained using the δ^{15}N method in Mexico by Crews (1993) were slightly lower than those found at the NB and PEI sites, while Bowman et al. (2003) found slightly higher values in Australia (Table 2.1).

There tended to be greater amounts of labile N applied as manure to the fields at the NB site than at the PEI site. Therefore, there is greater uncertainty in the assumption that the alfalfa sample with the lowest δ^{15}N had actually derived all of its tissue N from BNF. The field derived β value for alfalfa from NB, -0.73‰, was greater than the -1.50‰ value from PEI. If the PEI β value for alfalfa were used in determining the %Ndfa of the NB alfalfa, the overall mean %Ndfa for alfalfa from NB would be 65%, with a mean difference of 10% from the %Ndfa calculated with the NB β value (data not shown). The smaller %Ndfa values obtained using the PEI β value for alfalfa would result in 15% smaller measures for BNF-N $ha^{-1}cut^{-1}$ (data not shown).

Using the δ^{15}N method Carlsson et al. (2009) in Germany and Huss-Danell et al. (2007) in Sweden found %Ndfa over 80%. The 77% Ndfa measured for red clover in PEI was closer to the %Ndfa reported for red clover by Huss-Danell and Chaia (2005) and Høgh-Jensen and Schjoerring (1994).

Actual amounts of N fixed per hectare are highly correlated with legume dry matter yield, as legume productivity is one the most important factors in the amount of N fixed (Carlsson and Huss-Danell, 2003). The wide ranges in amounts of N fixed per hectare found in the literature can be attributed primarily to this relationship. A study investigating forage comprising of mostly, or entirely, one legume species will therefore show much larger total amounts of N fixed per hectare than a study investigating mixed forages with lower legume content. Carlsson and Huss-Danell (2003) reviewed studies measuring BNF rates in temperate climates for red clover and alfalfa and found ranges of 8-295 and 10-350 kg of N fixed per hectare per year, respectively. The relatively low proportion of legumes present in the forage fields in NB and PEI, often less than 50%, resulted in correspondingly low amounts of BNF-N fixed per hectare by red clover and alfalfa. Only two fields, DK3 in 2009 and 5678 in 2010, had more than 100 kg of N per hectare per year fixed by BNF. Fields DK3 and 5678 also had higher proportions of legumes to non-legumes in the DM yields in the years when fixed N was over 100 kg per hectare.

Comparison with the N balance method did not indicate consistent overestimates of BNF-N in the δ^{15}N method. This was a potential concern, as the field derived β values could have been derived from legumes with less than 100 %Ndfa due to the consistent applications of manure N. The estimate of N fixed present in legumes from the N balance method was based on the assumptions that 50% of grass N off-take was derived from N transfer and that the transferred N was derived entirely from BNF. This is likely an over estimate of N transfer, as the %Ndfa of the legume N likely applies to any N being transferred from the legume to the grass. Additionally, the upper range for the proportion of grass N off-take derived from N transfer was used; however in soil environments with abundant labile N, non-legume species would likely be less reliant on transferred N. An overestimation of transferred N would result in underestimation of the quantity of fixed N present in the legume N off-take by the N balance method.

2.4.3 Model Evaluation

The two models compared in this study are very similar. Whereas the Carlsson (2005) model is simply a constant to convert DM to fixed N, the Høgh-Jensen et al. (2004) model simply splits up the constant into separate parameters representing the principal factors which influence the fixed N content in DM, legume N concentration and %Ndfa. By maintaining distinct parameters for %N and %Ndfa the model is more versatile in application. Adjusting the Høgh-Jensen et al. (2004) model with parameters for %Ndfa and %N and condensing them into one constant, the adjusted Høgh-Jensen et al. (2004) model could be expressed as $N_{fixed} = DM \cdot 0.024$ for alfalfa. The Carlsson (2005) model for alfalfa is $N_{fixed} = DM \cdot 0.021$. Despite the models being very similar, the negative bias of the Carlsson (2005) model could result in consistent underestimation of BNF. The adjusted Høgh-Jensen et al. (2004) model is recommended for further use in assessing BNF rates of alfalfa in the Atlantic Canada region.

For red clover, the Carlsson (2005) model performed better than the original Høgh-Jensen et al. (2004) model according to the IoA and CoE. Both models were positively biased and tended to overestimate BNF. The adjusted Høgh-Jensen et al. (2004) model produced comparable IoA and CoE values to the Carlsson (2005) model; however the adjusted Høgh-Jensen et al. (2004) did not have as great of a positive bias as the Carlsson (2005) model. The adjusted Høgh-Jensen et al. (2004) model is recommended for further use in assessing BNF rates of red clover in the Atlantic Canada region.

2.5 CONCLUSION

The $\delta^{15}N$ results at both sites was consistent with similar studies which have investigated BNF in mixed grass and legume forages. The overall %Ndfa values obtained for alfalfa were close to those reported from other regions and the red clover %Ndfa was similar, if slightly lower, than other reported values. A distinguishing feature of the study sites was the manure N inputs applied to the fields. The availability of soil N is often cited as one of the most influential factors in BNF (Ledgard and Steele, 1992), so much so that some nutrient management programs differentiate N fixation estimates based on N inputs. The Nebraska Nutrient Balancer, a WFNB extension program, specifically excludes legumes from BNF input estimates if manure has recently been applied (Koelsch, 2001). The findings from both sites clearly indicate that significant amounts of N are fixed by forage legumes despite consistent applications of manure. However, the fixed N values which were used to verify the model predictions are based on the assumption that the lowest detected $\delta^{15}N$ values from the field are suitable substitutes for the actual β values. If the field derived β values are greater than the actual β for alfalfa or red clover plants relying on 100 %Ndfa, then the reported %Ndfa values in this study may be overestimations.

With adjustments to the %Ndfa and %N parameters, the Høgh-Jensen et al. (2004) model was able to provide BNF estimates with good agreement to the $\delta^{15}N$ measures for alfalfa and red clover. The adjustments made to the model were based upon data from the $\delta^{15}N$ BNF measures; therefore the alfalfa model may be slightly more robust as the data is drawn from four fields across two provinces. The red clover was only present at the PEI site; therefore further adjustments to the model may be warranted if more BNF data from red clover in the Atlantic Canada region is available in the future.

The models require DM yields of the specific legume species to calculate BNF-N inputs. In Atlantic Canada, forage legumes are grown predominantly in mixtures with grasses, therefore determining exact DM yields of legumes could be a challenge for estimating precise BNF-N inputs in WFNBs and other nutrient management plans. Influence of legume contents in forage on BNF-N inputs will be further explored in Chapter 3.

CHAPTER 3 WHOLE FARM NUTRIENT BUDGETS ON NB AND PEI DAIRY FARMS

3.1 INTRODUCTION

3.1.1 Whole Farm Nutrient Budgets

A whole farm nutrient budget (WFNB) is a nutrient management tool that can be used to account for the presence of both crop and animal production systems on commercial farms. A farmgate version of a WFNB accounts for those inputs and outputs crossing the boundary of the farm operation (dashed line in Figure 3.1). By assessing inputs and outputs without respect to their use (for crop or animal production) on the farm, a farmgate WFNB is able to measure the efficiency of nutrient utilization by the whole farm. A balance of the nutrient inputs to a dairy farm from external sources versus the nutrient outputs of the farm can be a quick indicator of nutrient use efficiency and risk of environmental damage (Wattiaux et al., 2005). Nitrogen (N) and phosphorus (P) are often the focus of WFNBs on dairy farms as these nutrients can be significant components of non-point source pollution (Hutson et al., 1998). Potassium (K) is not considered a potential pollutant; however, elevated concentrations of K in forages are the linked to the incidence of hypocacaemia and hypomagnesaemia in dairy cattle (Pelletier et al., 2006). Livestock operations with high livestock densities tend to have high soil K concentrations (Kayser and Isselstein, 2005), which may result in luxury consumption of K by crops produced for animal feeds.

Farmgate WFNBs of dairies from current literature are summarized in Table 3.1. Much of the published dairy farm WFNB data comes from surveys of dairies within geographic regions (Anderson and Magdoff, 2000; Spears et al., 2000a,b; Hristov et al., 2006; Roberts et al., 2008) and case studies of individual commercial or experimental dairy farms (Klausner et al., 1998; Aarts et al., 2000; Weller and Bowling, 2004; Lynch et al., 2003; Steinshamn et al., 2004; Kobayashi et al., 2010). A common measure used in WFNBs is nutrient use efficiency (NUE), calculated using the sum of all managed outputs as a percent of the sum of all the inputs. The NUE is calculated over a set period of time, usually one calendar year. WFNBs, particularly those investigating several consecutive years on a farm, rely on the assumption that farms are in a steady state. Changes to land area used in crop production or herd size affect the nutrient stores within the system components.

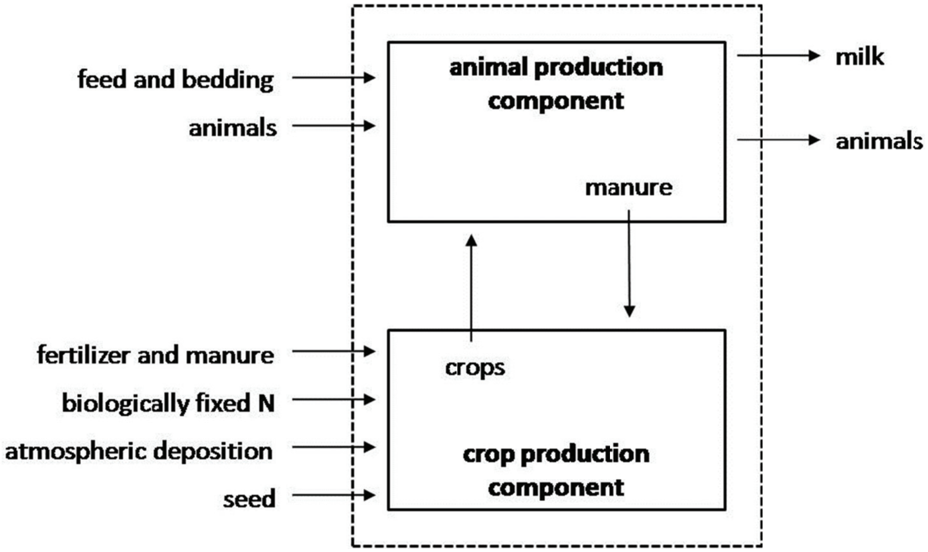

Figure 3.1 Dairy farm nutrient flows: farmgate boundary defined by dashed line, farm component boundaries defined by solid lines, only managed outputs shown in figure

The NUE is linked to the balance of nutrient inputs and outputs on a farm, where an NUE over or under 100% indicates a deficit or surplus of nutrients, respectively. A surplus of a nutrient on a farm and the related NUE is not entirely related to management or waste. A surplus can be considered in three components identified by Powell et al. (2010): the portion of inputs that is not incorporated into outputs due to biological limitations, the portion of inputs that is used to mitigate production risks, and the portion of inputs that is wasted. Losses of nutrients from the dairy farm through volatilization, leaching, denitrification, and runoff are commonly not quantified as outputs in WFNBs largely due to the difficulty in their measurement (Wattiaux et al., 2005) and uncertainties greater than 20% in their estimation (Oenema et al., 2003).

As the main contributors to nutrient inputs on dairy farms, feed imports (Anderson and Magdoff, 2000; Powell et al., 2001; Spears et al., 2003b) and BNF (Roberts et al., 2008; Spears et al., 2003a; Wattiaux et al., 2005) have considerable influence over NUE. If manure is exported from the farm system as an output, as was the case in many of the farms surveyed by Hristov et al. (2006), farm NUE tends to increase as the losses inherent in recycling manure nutrients are not incurred within the farm system.

The whole farm N-NUE has a fairly narrow range (14-41%) in reported studies in comparison with the P-NUE, which shows considerable variation with a range of 31-635%. K-NUEs also show a broader range of values than the N-NUE. Dairies relying on more off-farm feed tend to have lower whole farm NUE; both N (Powell et al., 2010) and P (Weller and Bowling, 2004; Roberts et al., 2008) NUEs are influenced by the amount of off-farm feed inputs used by farms. Farms with higher P and K-NUEs of over 100% typically produce all their own feed and often apply little to no fertilizer from off-farm sources.

An approach to WFNBs which investigates the cycling of nutrients within a dairy farm, as well as the overall balance of inputs and outputs, provides more opportunity for management interpretations beyond a simple risk or efficiency assessment. System WFNBs typically separate the farm into basic components and determine the flow of nutrients among components. In Figure 3.1, the model dairy farm is split into its animal and crop production components (APC and CPC), respectively. In contrast to a farmgate WFNB, a system WFNB assesses the inputs and outputs to the different components of the system, including those which do not enter or leave the farm. Unlike farmgate WFNBs which may in some cases be compiled entirely through farmer interviews, system WFNBs require much more detailed data collection. Data used in WFNBs is typically obtained from farmer records, estimates, and assumptions or data from actual measurements in the field. The type of data used to compile system WFNBs is rarely uniform across studies and is often a combination of different types of data (Oenema et. al., 2003). This can be attributed to different approaches and nutrient management tools in geographic areas and also to the different conditions and requirements of individual farm systems. Defined boundaries of the components of the farm system in a WFNB are important for interpreting NUEs and farm nutrient balances. The boundaries of farm components also influence the type of data and sampling methods which may be used in compiling the WFNB.

Table 3.1 Whole farm nutrient use efficiencies from selected farmgate whole farm nutrient budgets of dairy farms

		Farm NUE[‡] (%)			Balance (kg ha^{-1})			Livestock density (AU ha^{-1})
Source	**Source details**	**N**	**P**	**K**	**N**	**P**	**K**	
Bacon et al. (1990)	Two year average of case study in Pennsylvania	48	44	48	79	18	22	3.0
Paul and Beauchamp (1995)	Three year average of dairy and beef operation case study in Ontario	17			288			4.1
Dou et al. (1998)	Two case studies in Pennsylvania	29						1.7
Klausner et al. (1998)	One year New York case study	28	41	29	212	25	57	2.89
Aarts et al. (2000)	3 year average of De Marke experimental farm, Netherlands	36			166			2.9
Aarts et al. (2000)	Intensive commercial dairies in the Netherlands, 1980s	14			487			4.83
Anderson and Magdoff (2000)	Average from 43 dairies in north east US		43			22		1.52
Spears et al. (2003a,b)	Average from 23 commercial dairies growing crops in Utah and Idaho	28	42					
Lynch et al. (2003)	One year case study of an Atlantic Canada dairy	25	31	37	76	9	8	0.76
Weller and Bowling (2004)	Four year case study of an organic dairy in the U.K., no off-farm feed inputs	21	635	151	99	-5	-3	1.27
Weller and Bowling (2004)	Four year case study of an organic dairy in the U.K., some off-farm feed inputs	26	100	64	151	0	8	1.65
Steinshamn et al. (2004)	Three year average from an organic dairy operation in Norway	30	85		41	1		1.21
Roberts et al. (2008)	Two year average of 15 organic dairies in Ontario	21	84	38	75	1	11	1.00
Kobayashi et al. (2010)	Five year case study at a Japanese dairy research station	25	19	18	378	97	199	4.09

[‡] NUE: Nutrient Use Efficiency = Managed Outputs / Nutrient input, reported values are means for studies including more than one farm

1AU = 454kg animal

3.1.2 Crop Production Component

The assessment of nutrients flowing in and out of the CPC of dairy farms is where approaches to system WFNBs often differ. A variety of different methods are used in compiling system WFNBs , therefore the CPC NUEs presented in Table 3.2 should be interpreted with consideration for how the data have been compiled in each study. The CPC typically encompasses all the fields which are used to produce crop products on the farm. Crop inputs such as manure (whether generated on-farm or imported) and fertilizers are quantified at application and the harvested crops (whether used on-farm or sold) are considered as outputs. An input of conventional fertilizer may be quantified with reasonable certainty through farmer financial or application records and fertilizer nutrient analysis; however, materials without measured quantities or known analyses are more difficult to quantify. Oenema et al. (2003) classified inputs such as manure and harvested crop nutrient outputs in the CPC as having uncertainties of 5-20% in their WFNB quantification. Farmer application records and on-farm sampling for subsequent chemical analysis can be used to assess such nutrient flows. However, manure on dairy farms is stored for prolonged periods of time resulting in highly variable nutrient composition over time. Ammonium N is subject to loss through volatilization as ammonia gas (McGinn and Janzen, 1998) and nutrients may settle or precipitate, resulting in stratification of nutrient concentrations of manure in storage over time (VanHorn et al., 1994). The methods used for quantification of organic amendment volumes and sampling for nutrient analysis of inputs such as manure or composts will often reflect the way these inputs are managed and applied by the farmers themselves. A further complication in comparing system WFNBs is that some assess plant available nutrients in manure or other amendments rather than total amounts (Spears et al., 2003a,b), or correct manure N content for losses due to volatilization (Aarts et al., 2000, Steinshamn et al., 2004) resulting in higher NUE than in WFNBs which do not follow the same methods.

The NUEs presented in Table 3.2 indicate that consistent N and P surpluses occur in the CPC of dairy farms. However, the CPC NUEs (Table 3.2) tend to be greater than those reported for the farmgate WFNBs (Table 3.1). As previously mentioned for the farmgate NUEs, efficiency as determined by the system WFNB is comprised of portions related to system limitations as well as wasted nutrients. Considering that as much as 50% of the soluble N in livestock manure may be lost through volatilization (Janzen et al., 2003) and that the largest portion of volatilization occurs from the application of manure to land (McGinn and Janzen, 1998), CPCs with N-NUEs over 75% are reasonably efficient systems. Without significant pathways for loss from the CPC, low P and K-NUEs indicate nutrient surpluses are likely occurring.

Quantification of BNF inputs to the CPC has been identified as one of the largest uncertainties in WFNB (Watson et al., 2002; Berry et al., 2003; Spears et al., 2003a, Ross et al., 2008). Few studies employ the same methodology for quantifying BNF, though most use either a model or conversion factor to transform legume yields (Aarts et al., 2000; Weller and Bowling, 2004) or N off-take (Paul and Beachamp, 1995; Klausner et al., 1998; Steinshamn et al., 2004; Hristov et al., 2006; Roberts et al., 2008) to a quantity of BNF input. Each of the cited studies employing models or conversion factors used different forms of these methods for quantifying BNF. Dou et al. (1998) and Bacon et al. (1990) used the same conversion factor (60% of alfalfa N harvested as BNF-N) as Hristov et al. (2006); however, they did not differentiate between legume species or forages containing grass legume mixtures. Other WFNBs have used the difference between legume N off-take and the N available from inputs (Lynch et al., 2003; Spears et al., 2003a) as an estimation of BNF. A result of the different methods of estimating BNF is highlighted by Towns (2003, in Wattiaux, 2005) who indicate that the same farm using a WFNB program which estimates BNF based on differences between legume N off-take and the N available from inputs had nearly 300% greater BNF-N inputs than when using a WFNB program which estimates BNF based on conversion factors applied to yields of several categories of legume crops. The WFNB program which resulted in the much lower BNF value accounted for only BNF in fields which had not received N inputs from manure or fertilizer in two years. Therefore, WFNB results may be considerably influenced by not only the method of BNF estimation, but also the criteria under which BNF is considered as an input of N to the CPC.

As noted above, most quantifications of BNF-N inputs are based upon N off-take or yields of the legume crop. Thus, data derived from the harvested nutrient outputs of the CPC are used to quantify an input. If all of the BNF-N inputs accumulated in the harvested portion of legumes, then this method could be relied on with certainty. However, N is distributed, and in flux, between the above ground and the below ground tissues of perennial forage legumes throughout the growing season. Zebarth et al. (1991) found 68% and 41% of N in uprooted alfalfa and red clover plants, respectively, harvested at the second cut was below ground in root tissues. While the net quantity of N contained in root and stubble materials may remain constant for years in perennial forages, rhizodeposition and the immobilization of dead roots in mixed legume and grass swards contributes significant amounts of N to the soil N pool (McNeill et al., 1997; Rasmussen et al., 2007). Investigating forage mixtures of red and white clover with ryegrass, Høgh-Jensen and Schjoerring (2001) found the amount of N from rhizodeposition to be greater than the N harvested above ground. There are still uncertainties in attributing quantities of rhizodeposited N to specific forage species or to rhizodeposited N derived from BNF in forages containing mixtures of legume and non-legume plants (McNeill et al., 1997). Based on the work of Høgh-Jensen and Schjoerring (2001), Høgh-Jensen et al. (2004) suggested incorporating factors of 1.3 to 1.6 to BNF estimations based on aboveground legume yields depending on forage species and soil textures.

Table 3.2 Dairy farm crop production component (CPC) nutrient use efficiencies from system whole farm nutrient budgets

Source	Source details	CPC NUE[‡] (%)			Balance (kg ha^{-1})		
		N	P	K	N	P	K
Bacon et al. (1990)	Two year average of case study in Pennsylvania	75	75	101	86	14	-2
Paul and Beauchamp (1995)	Three year average of dairy and beef operation case study in Ontario	53			165		
Hutson et al. (1998)	One year New York case study	89	65		157	14	
Aarts et al. (2000)	3 year average of De Marke experimental farm, Netherlands	66			131		
Aarts et al. (2000)	Intensive commercial dairies in the Netherlands, 1980s	53			351		
Alfaro et al. (2003)	Grazed and harvested grasslands in south west England			69-123			-77-27
Spears et al. (2003a,b)	Average of 23 commercial dairies growing crops in Utah and Idaho[◊]	114	67		-	-	
Lynch et al. (2003)	One year from an Atlantic Canada case study	73			27		
Steinshamn et al. (2004)	Three year average of an organic dairy operation in Norway	89	166		12	-6	
Kobayashi et al. (2010)	Five year case study at a Japanese dairy research station	57	31	96	104	59	9

[‡] Nutrient use efficiency = managed outputs / nutrient inputs

[◊] NUEs only account for plant available N and P

Table 3.3 Dairy farm animal production component (APC) nutrient use efficiencies from system whole farm nutrient budgets

Source	Source details	APC NUE[‡] (%)			Balance (kg ha^{-1})		
		N	P	K	N	P	K
Bacon et al. (1990)	Two year average of case study in Pennsylvania	76	91	88	88	6	30
Paul and Beachamp (1995)	Three year average of dairy farm case study in Ontario	71			123		
Hutson et al. (1998)	One year New York case study	84	87		51	7	
Aarts et al. (2000)	3 year average of De Marke experimental farm, Netherlands	97			9		
Aarts et al. (2000)	Intensive commercial dairies in the Netherlands, 1980s	79			105		
Lynch et al. (2003)	One year from an Atlantic Canada case study	59			49		
Steinshamn et al. (2004)	Three year average of an organic dairy operation in Norway	83	92		15	2	
Gustafson et al. (2007)	Swedish dairy operating separate organic and conventional milk production	81	108	86	33	-2	20
Kobayashi et al. (2010)	Five year case study at a Japanese dairy research station	51	65	62	244	18	139

[‡] Nutrient use efficiency = outputs (milk+meat+manure) / inputs (feed+bedding+purchased livestock)

3.1.3 Animal Production Component

In contrast to the CPC, where the assessment of nutrient flows may differ among WFNBs, the boundaries used to define which farm components make up the APC often differentiate WFNB approaches. Simply dividing a dairy system into the CPC, and grouping all remaining components, such as feed and manure storage, animals and their housing, into the APC is often used in system WFNBs such as Paul and Beauchamp (1995) and Lynch et al. (2003). These boundary definitions within the dairy system are presented in Figure 3.1. If a separate WFNB component is defined for manure storages such a difference should be accounted for when comparing APC NUEs. In Table 3.3 NUEs have been compiled from the literature and where enough data was available, standardized so that the APC boundaries are comparable. A N-NUE for an APC which does not include manure storage would likely have a much higher N-NUE than one which includes the N loss from volatilization which occurs during manure storage. Another important distinction should be considered between a feed to milk or herd efficiency and the APC NUE. Whereas feed conversion efficiency considers only feed inputs and the milk or meat product outputs, an APC NUE includes nutrient inputs which are used in production but may not enter the animals (e.g. bedding), and manure as an additional output. Herd efficiencies considering only milk or meat products are much lower than APC NUEs as quantified in this study. In comparison with the higher APC NUE values presented in Table 3.3, Spears et al. (2003a,b) found average N and P herd efficiencies of 20% and 30%, respectively, for 23 dairy farms feeding some home grown feed.

3.1.4 Objectives

The specific objectives of this study are for one commercial dairy farm in each of NB and PEI to:

1. Quantify the annual N, P, and K inputs to and managed outputs from the crop and animal components of each dairy farm for a two year period.

2. Calculate nutrient use efficiencies of N, P, and K of the whole farm and farm components and compare with efficiencies in the published literature.

3.2 MATERIALS AND METHODS

3.2.1 Farm site descriptions

One representative dairy farm from PEI and NB were selected for system WFNBs of N, P and K. The farms were selected from a larger group of dairy farms participating in a regional farmgate WFNB study. To ensure concurrence with the assumption that the farm systems are in a steady state, farms were chosen for the system WFNBs based on the following criteria: constant land base, constant animal numbers, and constant management practices. Consistent record keeping practices and the ability to represent typical farms from their region were also considerations for farm selection. Basic characteristics of the chosen farms are presented in Table 3.4.

Table 3.4 Livestock and cropping characteristics of NB and PEI farm sites

	NB site		PEI site	
	2009	**2010**	**2009**	**2010**
Milk cows	93	88	49	50
Livestock density (AU[‡] ha^{-1})	1.20	1.33	1.20	1.36
Milk production (L cow^{-1} yr^{-1})	9,404	10,536	10,716	11,002
Land-base (ha)	161	161	88	82
Land utilization:				
Forage (%)	82	79	62	50
Pasture (%)	10	10	2	2
Oats (%)	8	11		
Barley (%)			21	29
Corn (%)			15	19
Dairy Ration (DM)				
Crude protein (%)	16		17	
Phosphorus (%)	0.48		0.37	
Potassium (%)	1.5		1.3	

[‡]Animal unit = 454kg live animal weight

The PEI farm site was located in the northwest of the province near Foxley River. The fields used in crop production on the farm were Haliburton and Kildare soils (classified as Orthic Humo-Ferric Podzols), which are well drained, sandy loam to fine sandy loam soils (MacDougall et al., 1988). Crops produced on-farm were all used for feed and bedding by the dairy herd and followed a corn-barley-perennial forage rotation. Perennial forage (red clover, alfalfa and grass mixture) was undersown in barley and typically remains as forage for five years. A small exercise yard for dry cows was the only pasture present on the farm. Forage fields were harvested as chopped silage and roundbale hay, and corn was ensiled. Silages were stored in silos; however excess silage was stored under plastic outdoors. Animals were fed a total mixed ration (TMR) comprised of on-farm produced feeds as well as purchased barley and supplements. Semi-solid manure from the dairy barn was stored in a walled shed, while solid manure from the heifer barn was stored outdoors on a concrete slab. The dairy herd was closed and comprised entirely of purebred Holsteins. The main off-farm nutrient inputs were animal feeds and fertilizers for barley and corn.

The NB farm site was located in the southeast corner of the province near Perry Settlement. The fields used in crop production on the farm were Salisbury (classified as Podzolic Grey Luvisols) and Cornhill (classified as Orthic Humo-Ferric Podzols) soils, which are loam to sandy clay loam soils (Fahmy et al., 2010). Mixed alfalfa and grass forages and small quantities of oats were produced on-farm. The forages were mostly used for wrapped roundbale silage, and a small amount of hay. Two fields were used as large pastures for dry cows and heifers from late spring to fall. Oats produced were not used on the farm; however, oat straw was used as bedding. Forages produced on-farm were supplemented with purchased dairy concentrates. Liquid manure from the dairy barn was stored in an uncovered lagoon. Solid manure from the heifer barn was stored outside in the winter and spread as produced in the spring, summer and fall. The dairy herd was all Holstein, but open and not registered. The main off-farm nutrient inputs were feed concentrates and large volumes of liquid hog manure.

The WFNBs on each farm were compiled over a two-year period beginning January 1, 2009. The WFNBs were recorded on a yearly basis; therefore, nutrients that were imported, or produced on each farm in the previous year were identified by a nutrient (N, P, and K) inventory at the beginning of each year. Farmer participants were selected in March of 2009; therefore, the starting inventories for 2009 were estimates obtained from farmers in March of that year. Feed, fertilizers, bedding and any other materials left over from the previous year were quantified. Livestock numbers, number of milking cows, dry cows, heifers, and calves on each farm were also recorded at the time of the nutrient inventories. Microsoft Excel 2007 was used to compile the WFNBs.

3.2.2 Crop Production Component Nutrient Flows

Where possible, at each farm, fields similar in soil type, phase in crop rotation, and crop composition were grouped together for analysis. Inputs and outputs to the CPC were assessed at the individual field or field group level. The overall CPC budget at each farm site was compiled by aggregating nutrient budgets from all fields used in crop production across the farm.

3.2.2.1 CPC Inputs

Quantities of any synthetic fertilizer (PEI farm only) and seed inputs used in each field of the CPC of the farm were determined from records maintained by the farmers. Manure produced on-farm was sampled immediately prior to application. At the NB site 2 L samples were obtained as the liquid manure was pumped from the lagoon into the tank spreader, or directly from the box spreader for solid manure. The capacity of the tank spreader at the NB site was 15,000 liters, and drive on scales were used to determine the weight of box spreader loads (2.3 tonnes per load). At the PEI site, 2 L composite samples of semi solid and solid manure where obtained from the storages at the time of application. The load quantity of the side slinger manure spreader at the PEI site had been previously determined prior to this project as 7 tonnes by provincial specialists using drive on scales. When possible, two samples were obtained per type of manure used in each spreading period (spring, summer or fall). The number of loads applied per field was obtained from farmer records. Manure samples were frozen for storage, and then sent for analysis of total N, P, and K at the Nova Scotia Department of Agriculture, Laboratory Services in Truro, Nova Scotia.

Manure N, P, and K deposited in pastures by dry cows and heifers was determined by daily manure production values published by the ASABE (2010) presented in Table 3.5. Estimates based upon the ASABE values represented approximately 7% and 2% of the manure nutrients included in the NB and PEI budgets, respectively. At the NB site, liquid hog manure was imported from a nearby farm in 10,000 gallon (37,850 litre) loads. The hog manure was mixed with the liquid dairy manure in storage prior to application. The number of loads imported was obtained from farmer records, and samples of the hog manure were obtained as it was pumped into the manure lagoon. Despite the manure storages being contained within the APC, the hog manure was considered as an input to the CPC (i.e. as it was not an internal APC output but rather a direct external input to fields).

Table 3.5 Daily manure N, P, and K production for cows on pastures

	Daily excretion per cow (kg day^{-1})		
	N	**P**	**K**
Dry Cow	0.23	0.03	0.15
Heifer	0.12	002	0.11[‡]

Adapted from ASABE standards, 2010

[‡] No values were available for heifer K excretion, therefore heifer K excretion was adjusted based on similar K content in dry cow diets and smaller DM intake

The deposition of N from the atmosphere onto lands not adjacent to significant sources of N emissions has been estimated to be 5 kg N ha^{-1} across Canada (Janzen et al, 2003). Neither farm was located near areas of concentrated animal production. While the farms themselves are sources of N emissions, Janzen et al. (2003) state that any N emitted from the farms that is deposited into the soil through deposition is essentially being cycled back into the farm system, therefore an estimate of 5 kg N ha^{-1} is suitable.

In Chapter 2, models were tested to determine which could best predict BNF-N inputs to perennial forage fields at the farm sites. The parameters of the model from Høgh-Jensen et al. (2004) were adjusted based on measurements of forage BNF-N detailed in Section 2.3.3 to obtain the following models shown in Table 3.6 for estimating BNF-N based on legume dry matter (DM) yields. DM yields of the forage legumes were obtained from CPC output measurements described in the next section. The DM yields are representative of the BNF-N leaving the field as harvested crop; therefore to be fully inclusive of BNF-N inputs to the CPC, rhizodeposition factors proposed by Høgh-Jensen et al. (2004) are multiplied by the BNF-N yield to obtain a total BNF-N input. BNF-N inputs were not calculated for legumes underseeded in grain crops. Hannaway and Shuler (1993) indicate that while nodules are beginning to form during legume establishment there is little BNF. Additionally, from field observations, legumes rarely represented more than 5% of the overall harvest from grain fields.

Table 3.6 Adjusted Høgh-Jensen et al. (2004) models used for estimation of biological N fixation derived N

Legume species	Model for BNF-N[◊]	Rhizodeposition factor[‡]
Red clover	kg N_{fixed} = DM x 0.032 x 0.77	1.60 – 1.30
Alfalfa	kg N_{fixed} = DM x 0.034 x 0.72	1.50 – 1.25

[◊] where the model is kg N_{fixed} = DM x %N x %Ndfa, DM is the dry matter yield of the legume in kg

[‡] high values for clay soils, factor decreases in coarser textured soils

3.2.2.2 CPC Outputs

The only measured output from the CPC was harvested crops. In perennial forage fields four 0.5 m^2 quadrats were clipped immediately prior to each harvest from each field or field group to provide samples for assessing the above ground nutrients that left the field as harvested crops. Fifteen quadrats were harvested from two of the fields at each site throughout the study for the assessment of BNF inputs discussed in Chapter 2.

At the NB site the farm obtained two cuts from 15 forage field groups in 2009. Ten field groups were sampled immediately prior to the first cut in June, and 14 prior to the second cut in August (96 quadrat samples total). However, harvest times in 2009 were not optimal and rain delayed some fields by several weeks. Additionally, the NB farm typically harvests three cuts per year but opted for two cuts to prioritize a new member of the family in the fall of 2009. In 2010, the NB farm obtained two cuts from

17 field groups, and a third cut from eight of the field groups. Sixteen of the 17 field groups were sampled prior to the first and second cuts in June and late July, and seven of the eight field groups were samples prior to the third cut in September.

At the PEI site field groups were used more than the individual field budgets which comprised most of the NB CPC data. Forage fields were grouped according to their stage in rotation. In 2009 quadrats were harvested from all first and two thirds of the second cut forage field groups at the PEI site. Composite samples were obtained from windrows in fields that were cut before quadrats could be harvested. Fewer fields were harvested for the second cut in 2009 as several fields which were to be planted to corn the following year were left with standing forage over the winter. A rented field was also dropped in the summer of 2009, yielding only one cut for forage. Quadrat samples were obtained from all forage field groups prior to harvest at the PEI site in 2010.

The fields ranged in size from < 2 to 14 hectares, with some of the larger fields containing variable topography and plant composition. Quadrats were harvested from areas in the fields or field groups which would provide a representative sample of the forage present in the fields; however, the actual placement of the quadrats was determined by throwing the quadrat behind the head to eliminate some sampling bias. Forage samples were clipped at 3-5 cm based on the cutting heights used by farmers. Plant samples were kept cool until they could be weighed and dried, typically within 3 days of harvest. Entire plant quadrat samples were dried at 60°C. Dried samples were weighed to calculate forage DM content and DM yield. The legume composition (% alfalfa and % red clover) of each quadrat was visually estimated at harvest and recorded. In the event that a field was cut prior to quadrat sampling, a composite of grab samples were taken from windrows if they were still present to obtain a nutrient content analysis.

For each cut, an average N, P, and K concentration from all the forage samples was calculated at each site and used if no samples were obtained for a field or field group. Farmer records for yields, in bales or loads per field, were obtained to verify the yield measurements of the quadrats and for use in the event that fields were cut prior to quadrat sampling. In addition, four forage fields (two at each site) were studied in detail for Chapter 2 and over the course of the project 270 quadrat samples from these fields were sorted into alfalfa, red clover, grass and weeds and then dried. The exact composition of these quadrats was used to verify biases in the visual estimation of legume content. Dried forage samples from each quadrat were analyzed for total N, P, and K (see section 3.2.4).

Forage yields from grazed pastures in NB were measured using the exclusion method as described in Bowman (2004) with slight modifications. Briefly, three 1m x 1m x 0.4m cages were placed in each pasture to prevent any grazing by cattle on the caged area. Sampling sites were chosen that provide a representative sample of topographic and vegetative elements of the pasture. Herbage samples were collected from a 0.5 m^2 quadrat three times per season from each exclosure. Visual estimates of quadrat legume content in the exclosures were noted prior to clipping. The samples were dried, weighed and analyzed for concentrations of total N, P, and K.

In 2009 field samples were not obtained from grain crops; therefore, farmer records for grain yields were used. Composite samples of grains and straw were obtained from the feed and bedding stores on the farms. In 2010, grain fields or field groups were sampled using the quadrat method. The same sampling methodology for sampling as used for forage samples was employed with the grain crops at both sites. Quadrats were harvested close to the harvest date of the crops. Samples were threshed with a combine harvester to obtain separate grain and straw samples from each quadrat. At the NB site, data was maintained for individual fields (4 quadrats per field); whereas the barley fields were considered together as one crop group at the PEI site (7 quadrats across the barley crop group). The samples were analyzed for concentrations of total N, P, and K as described in section 3.2.4.

Silage corn was sampled at harvest in October, immediately after harvest. Composite samples taken from truckloads of silage were analyzed for DM content and concentrations of total N, P, and K. Five samples were obtained from separate truckloads in 2009, and 6 in 2010. The same trucks were used to haul silage both years and in 2010 drive on scales were used to weigh loads of silage. Load weights, DM content from each load and the number of loads obtained from farmer records were used to calculate the DM yield of silage corn. All fields planted to corn at the PEI site were treated as one crop group.

From each quadrat sample nutrient concentrations and DM yield data was used to obtain an estimate of the N, P, and K off-take per harvest. For each field, or field group, the quadrat data was then averaged by cut and added together to obtain an estimate of crop N, P, and K off-take for the year. Although most of the crops harvested at each site were used by the dairy herd, the amount and source of any crop products leaving the farm was obtained from farmer records to be included as an output at the farmgate level.

3.2.3 Animal Production Component Nutrient Flows

In this study, the APC encompasses the dairy herd and the manure and storages on-farm as depicted in Figure 3.1. In contrast to the field or field groups used to assess the CPC, the APC was treated as one unit. However, there are more flows of nutrients to account for into and out of the APC.

3.2.3.1 APC Inputs

To properly determine the exact nutrient quantities entering the APC, materials containing N, P, or K that are carried over from one year to the next and used within the APC should be adjusted by the nutrient inventories carried out at the beginning and end of the budget period. However, the data from the N, P, and K inventories of farm produced forage was not sufficiently reliable to adjust forage inputs to the APC to create a flow of NPK exactly as fed to the dairy herd. The initial 2009 inventory was completely estimated due to the project timeline and the variety of round bale sizes used on the farm added uncertainty to inventory quantities calculated based on bale numbers remaining in storage. In both years of the study the farms changed from feeding first cut to second cut forage in early January. The 12 month budget period therefore included on-farm produced crop inputs to the APC from the second cut of the prior year, and first cut of actual budget year. The nutrient inventories would essentially dictate half of the crop inputs per year, introducing considerable uncertainty to the budget. The crop outputs from the CPC were therefore used unadjusted from each 12 month budget period as the crop input to the APC. The crop outputs from the grain fields in the CPC were separated into straw and grain fractions. At the NB site only the straw was considered as an input to the APC as the grain was stored on-farm but not consumed by the dairy herd. At the PEI site both the straw and grain were inputs to the APC.

Quantities of feeds (grains, supplements, concentrates, minerals) or bedding brought into the barn from an outside source were determined from farmer records. Any materials without an analysis from suppliers or consultants were analyzed for total N, P, and K (see section 3.2.4). The quantities of nutrients fed from crops produced on-farm was assessed by adjusting the amounts produced (obtained from output measurement of the CPC) during the twelve month budget period for amounts observed at the beginning and ending nutrient inventories. The number of any animals brought onto the farm was recorded, and nutrient composition of the average live weights was estimated using the following values: 0.08 % N (Maynard et al., 1979), 0.075% P (Anderson and Magdoff, 2000), and 0.015% K (Maynard et al., 1979).

3.2.3.2 APC Outputs

The quantity of milk shipped off the farm was obtained from monthly records from the Atlantic Dairy Livestock Improvement Corporation (NB site) and the Dairy Farmers of PEI (PEI site). The average protein content of each monthly milk shipment is noted in milk records, therefore total N was obtained using the standard conversion factor where N is protein divided by 6.38. Wu et al. (2001) indicate that milk P content varies from 0.06% to 0.13% and is strongly influenced by casein, which about half of the P in milk forms complexes with. Milk P content can be estimated by the formula %P =

0.0146*x* + 0.0487, where '*x*' is the percent of protein in the milk (Wu et al., 2001). Milk K is relatively constant and can assessed as 1.10 g K kg^{-1} $milk^{-1}$ (Maynard et al., 1979). The number and average live weight of cows and calves leaving the farm was obtained from farmer records. Nutrient composition of animals leaving the farm was estimated as stated above for the APC inputs. The quantity of manure leaving the APC of each farm was determined using data obtained from the CPC manure inputs. Therefore, the manure outputs from the APC do not represent strictly excreted nutrients from the dairy herd, but also include nutrients from bedding material and feed as well as losses of nutrients, such as N volatilization during the storage and handling of the manure. At the NB site, the N, P and K quantities from the imported hog manure were subtracted from total land applied quantities to obtain the output of manure from the APC.

3.2.4 Nutrient Content Analysis

When a nutrient analysis of an input material was not readily available, such as purchased bedding, or generic feeds, composite samples were taken for analysis. All samples were dried at 60°C to determine DM content. The dried generic input samples as well as all on-farm crop quadrat samples were ground to pass a 1 mm screen using a Wiley Mill. A 0.05-0.1 g subsample of the ground samples was analyzed for total N by dry combustion using a LECO 1000 CNS analyzer (Lynch et al., 2004). Inductively coupled plasma spectroscopy (ICP) was used to determine total P and K in the plant tissue samples. Samples were dry ashed and digested at the NSAC Organic Agriculture Research lab, and then sent to an external lab for ICP. The plant tissue dry ashing procedure was developed by Michael Main and based upon a method in Westerman (1990). Briefly, 0.5 ± 0.05 g of each sample was weighed into a ceramic crucible, then slowly warmed over a 2 hr period up to 550°C in a muffle furnace. The samples were combusted at 550°C for approximately 4 hours until no organic residues could be seen. After cooling, 10 mL of a 10% HNO_3 and 30% HCl acid digest were added to the crucible, and the solution heated briefly to approximately 50°C on a hot plate. Four mL of supernatant was pipetted from the crucibles, diluted and sent to PEI Analytical Laboratories in Charlottetown, PEI for the ICP analyses.

3.2.5 Soil Nutrient Levels

Stores of N, P, and K in the soil are not a separate component of the WFNB; however, historical soil data provided by the farmers and samples taken throughout the study were used for reference. The NB farm site began maintaining detailed soil records in 2005 for nutrient management planning. At the NB farm site, the farmer traditionally sampled each field in the late fall every two to three years for nutrient management planning. At the PEI site, fields intended for corn or barley were typically sampled every year to produce fertilizer recommendations for these crops. Additional composite soil samples (0-15 cm) were taken at each farm site (sampling was timed to match farmer practices) to obtain more soil nutrient data for the duration of the study. Historical soil test data and 2010 soil sample analyses were obtained from provincial laboratories (NB and PEI) which both used Mehlich III extractions for available P and K concentrations. Mehlich III extractions of the 2009 soil samples were carried out at the NSAC Organic Agriculture Research lab and sent to the PEI Analytical Laboratories carried in Charlottetown, PEI for ICP analyses.

At the NB site each field was rated as low, medium, medium high, high, and very high according to the ranges for soil test P and K from the NB Crop Fertilization Guide (Anonymous, 2001). Mean soil test P and K concentrations of all fields were used for interpretation at the PEI site as the year to year soil sampling was not consistent.

3.2.6 Calculation of the system whole farm nutrient budget

The APC was analyzed as one complete unit at each farm site; however subcomponents within the CPC were divided by crop type. Total nutrient quantities per field or field group were aggregated and then divided by the total area used in the CPC or individual crop subcomponent. Nutrient flows for the farm as a whole and for the APC and CPC subcomponents were quantified on a per ha of total crop land basis.

NUEs of N, P, and K for the whole farm (farmgate level) and individual farm components were calculated. The farmgate NUE is presented as the total of the managed nutrient outputs leaving the farm expressed as a percentage of the total nutrient inputs entering the farm (adjusted by any nutrients noted in the nutrient inventories) during a 12 month budget period. The NUE of a farm component is similarly a total of the managed nutrient outputs produced by CPC or APC expressed as a percentage of the total nutrient inputs to the component during a 12 month budget period.

3.3 RESULTS

3.3.1 Whole Farm Nutrient Budget - NB Farm Site

3.3.1.1 NB Crop Production Component

The average nutrient budget of the forage fields (including pastures) is presented in Table 3.7. Inputs of manure N, P, and K of forage fields were greater in 2010 than in 2009 (Table 3.7), even though the nutrient content of the mixed dairy and hog manure applied to fields was similar both years (Table 3.8). The average legume content in forage fields, which is used to determine legume DM yields for calculation of the BNF-N, declined from 2009 to 2010. BNF-N represented 31% and 20% of N inputs to forage fields in 2009 and 2010, respectively. The total DM yield of forage produced on the farm was greater in 2009; however, the N, P, and K uptake from forage did not always follow the same trend. Like the forage DM yield, P and K uptake were greater in 2009 than in 2010; however, N uptake was greater in 2010. All forage fields had net surpluses of N and P in both 2009 and 2010. A net deficit of K was observed in 2009; however, the following year greater K inputs and lower crop K uptake resulted in a net surplus.

In 2010 larger manure inputs to oat fields changed the oat nutrient budget results from nutrient deficits in 2009 to small surpluses in 2010 (Table 3.9). However, oat NUE values were higher than forages in both years, particularly in 2009 when NUE values over 100% (and associated net deficits) were calculated for N, P, and K. The oat fields received less manure than most forage fields; however, the oat fields would have benefited from residual nutrients from the plow-down of the forage present in the spring. The nutrient benefit from the plow-down remained within the CPC of the farm and was therefore not included as an input from an outside source.

Approximately 80% of the CPC was forage; therefore, the overall CPC nutrient budget (Table 3.10) closely resembles that of the forage fields (Table 3.7). Changes in the CPC nutrient balance and NUE values from 2009 to 2010 were related to changes in BNF-N input and crop off-take noted for the forage fields. In both years N and P were in surplus; however, the P surplus in 2010 was twice that of the 2009 surplus. Nutrient inputs from seeds were present only in oat fields and were very small when averaged across the entire area of the CPC.

Table 3.7 Nutrient budget for forage fields at the NB site in 2009 and 2010

	2009			2010		
Average alfalfa content [‡]	29%			22%		
Combined areas of all fields (ha)	148			143		
Average forage DM yield[‡] (t ha^{-1})	7.6			6.8		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:	kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}		
Manure	170	34	134	186	37	146
Biological N fixation	80			47		
Atmospheric N deposition	5			5		
Total inputs	**255**	**34**	**134**	**238**	**37**	**146**
Outputs:						
Crop off-take	125	26	155	147	22	120
Total managed outputs	**125**	**26**	**155**	**147**	**22**	**120**
Net balance	130	8	-21	91	15	26
Nutrient Use Efficiency[◊]	**49%**	**76%**	**116%**	**62%**	**59%**	**82%**

[‡] Visual estimate of the proportion of alfalfa plants in forage, excluding pastures, average weighted by field area

[◊] Managed outputs / inputs (%)

Table 3.8 Total N, P, K, and ammonium N concentrations of manure from NB site in 2009 and 2010

	Liquid Dairy[‡]			Dry Heifer	Liquid Hog
	Spring	Summer	Fall		
2009					
Total N %	0.27	0.28	0.32	0.48	0.40
Ammonium-N %	0.13	0.14	0.16	0.10	0.30
P %	0.05	0.05	0.07	0.09	0.08
K %	0.19	0.22	0.27	0.42	0.17
2010					
Total N %	0.28	0.31	0.25	0.52	0.35
Ammonium-N %	0.14	0.17	0.13	0.14	0.26
P %	0.06	0.07	0.05	0.08	0.08
K %	0.25	0.24	0.17	0.45	0.13

[‡] Liquid dairy manure combined with varying amounts of liquid hog manure

Table 3.9 Nutrient budget for oat fields at the NB site in 2009 and 2010

	2009			2010		
Combined areas of all fields (ha)		13			18	
	N	P	K	N	P	K
Inputs:		kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}	
Manure	29	5	20	77	15	59
Biological N fixation						
Atmospheric N deposition	5	0	0	5		
Seed	3	1	1	3	< 1	1
Total inputs	**37**	**6**	**21**	**85**	**15**	**59**
Outputs:						
Crop off-take	54	9	51	71	13	52
Total managed outputs	**54**	**9**	**51**	**71**	**13**	**52**
Net balance	-17	-3	-30	14	2	7
Nutrient use efficiency[‡]	**146%**	**150%**	**243%**	**84%**	**87%**	**88%**

[‡] Managed outputs / inputs (%)

Table 3.10 Nutrient budget for the crop production component at the NB site in 2009 and 2010

	2009			2010		
Combined areas of all fields (ha)		161			161	
	N	P	K	N	P	K
Inputs:		kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}	
Manure from farm	100	20	101	124	23	118
Imported hog manure	59	12	24	50	12	19
Biological N fixation	73			42		
Atmospheric N deposition	5			5		
Seed	< 1	< 1	< 1	< 1	< 1	< 1
Total inputs	**237**	**32**	**125**	**221**	**35**	**137**
Outputs:						
Crop off-take	118	25	145	139	21	113
Total managed outputs	**118**	**25**	**145**	**139**	**21**	**113**
Net balance	119	7	-20	82	14	24
Nutrient use efficiency[‡]	**50%**	**78%**	**116%**	**63%**	**60%**	**82%**

[‡] Managed outputs / inputs (%)

3.3.1.2 NB Animal Production Component

The farm produced crops were the largest flows of N, P, and K into the APC and manure was the largest flow out of the APC (Table 3.11). Roughly four times as much N and P left the APC as manure than as milk. Manure K outputs were almost 20 times greater than milk K. N, P, and K were in surplus both years in the APC. N surplus was greater in 2010 than in 2009, while P and K surpluses were greater in 2009 than in 2010.

Table 3.11 Nutrient budget for the animal production component at the NB site in 2009 and 2010

	2009			**2010**		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:		kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}	
Purchased feed concentrates	61	16	23	74	18	25
Bedding	2	< 1	4	4	1	5
Crops produced on-farm	112	24	139	138	20	112
Total inputs	**175**	**40**	**152**	**216**	**39**	**141**
Outputs:						
Milk	28	5	6	29	6	6
Animals	2	< 1	< 1	3	< 1	< 1
Manure spread off-farm	9	2	6	3	1	2
Manure spread on-farm	100	20	101	108	23	118
Total managed outputs	**139**	**27**	**113**	**143**	**30**	**126**
Net balance	36	13	39	72	9	15
Nutrient use efficiency[‡]	**79%**	**68%**	**74%**	**66%**	**77%**	**89%**

[‡] Managed outputs / inputs (%)

3.3.1.3 NB Farmgate Whole Farm Nutrient Balance

N and P-NUE values were very similar at the farmgate level in 2009 and 2010 (Table 3.12). However K-NUE was greater in 2009 than in 2010. The actual N, P and K surpluses were similar both years. Feed concentrates were the largest source of N, P and K inputs both years. The hog manure nutrient inputs were similar both years and followed feed closely as a main contributor to the nutrient inputs. Inputs of BNF-N were also close to the same magnitude as feed and manure inputs; however, the BNF-N input was higher in 2009 than in 2010. Outputs of manure and crops represented a significant portion of the outputs in 2009; whereas the following year only a small amount of manure was exported. Although the change in crop and manure outputs did not greatly impact N or P NUE values, the exported crops and manure represented 60% of K outputs in 2009 and only 25% of K outputs in 2010.

Table 3.12 Farmgate whole farm nutrient budget at the NB site in 2009 and 2010

	2009			2010		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:		kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}	
Feed	61	16	23	74	18	25
Bedding	1	< 1	1	1	< 1	1
Seed	< 1	< 1	< 1	< 1	< 1	< 1
Hog manure	59	12	24	50	12	19
Biological N fixation	73			42		
Atmospheric N deposition	5			5		
Total Inputs	**199**	**28**	**48**	**172**	**30**	**45**
Outputs:						
Milk sales	28	5	6	29	6	6
Livestock sales	2	< 1	< 1	3	< 1	< 1
Manure exports	9	2	6	3	1	2
Crop sales	4	1	5	0	0	0
Total managed outputs	**43**	**8**	**17**	**35**	**7**	**8**
Net balance	156	20	31	137	23	37
Nutrient use efficiency‡	**22%**	**29%**	**35%**	**20%**	**23%**	**18%**

‡Managed outputs / inputs (%)

3.3.1.4 NB soil test P and K levels

In comparison to the initial soil tests in 2005, there was a smaller area with very high (>78 ppm) soil test P in 2008, 2009 and 2010 (Table 3.13). After increasing from 2005 to 2008, the medium soil test P category (59-78 ppm) accounted for a larger on the farms than any other from 2008 to 2010.

Most of area at the NB site was in the medium soil test K category (Table 3.13). In 2010 there was a greater area rated with medium high and high soil test K concentrations than in previous years.

Table 3.13 Percent of farm field area at the NB site rated with low, medium, or high soil test P and K levels

	2005	2008	2009	2010
Total area (ha)	137	161	161	161
No. of fields sampled	21	25	25	25
Soil Test P[‡]				
Low (<20ppm)	0	0	0	0
Medium (20-58 ppm)	26	50	58	46
High (59-78 ppm)	44	18	20	38
Very high (>78 ppm)	30	32	22	16
Soil test K[‡]				
Low (< 38 ppm)	1	14	0	4
Medium (38-74 ppm)	56	73	72	56
Medium high (75-112 ppm)	23	13	22	26
High (>112 ppm)	20	0	6	14

[‡] nutrient level categories from the NB Crop Fertilization Guide (Anonymous, 2001).

3.3.2 PEI Farm Site

3.3.2.1 PEI Crop Production Component

The average nutrient inputs and outputs to forage fields are weighted by the land area of each field group. Inputs of manure N and P to forage fields were greater in 2009 than in 2010 (Table 3.14). The farm traditionally applies manure to forage fields only between first and second cut during the summer, followed by some fall application to fields at the end of the rotation. However; in 2009, manure was also applied to some forage fields in the spring. The semi-solid dairy manure had a slightly higher P content in 2009, whereas the K content was higher in 2010 (Table 3.15). This change in P and K contents resulted in the lower K manure inputs in 2009 than 2010 despite higher application rates in 2009.

Table 3.14 Nutrient budget for forage fields at the PEI site in 2009 and 2010

	2009			2010		
Average alfalfa content [‡]	15%			11%		
Average red clover content[‡]	12%			29%		
Combined areas of all fields (ha)	56			43		
DM yield (t/ha)	6.1			6.6		
	N	P	K	N	P	K
Inputs:	kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}		
Manure	143	29	73	117	18	77
Biological N fixation	50	0	0	96	0	0
Atmospheric N deposition	5	0	0	5	0	0
Total inputs	**198**	**29**	**73**	**220**	**18**	**77**
Outputs:						
Crop off-take	123	17	127	164	19	114
Total managed outputs	**123**	**17**	**127**	**164**	**19**	**114**
Net balance	75	12	-54	56	-1	-37
Nutrient use efficiency[◊]	**62%**	**59%**	**174%**	**75%**	**106%**	**148%**

[‡] Visual estimate of the proportion of alfalfa or red clover plants in forage, excluding pastures, average weighted by field area

[◊] Managed outputs / inputs (%)

Recently established fields near the beginning of their rotation as forage had more predominant red clover stands than alfalfa, whereas in older forage fields the red clover diminished and alfalfa became the predominant legume. In 2009, most of the forage fields were later in the rotation which resulted in the low red clover contents for the overall forage components. In 2010, the farm shifted their cropping proportions slightly to a greater emphasis on corn and barley. Consequently, the older forages from 2009 were either plowed and planted to corn, or not used in crop production. The 2010 legume contents show this shift to younger stands of forage with higher red clover content, and higher legume content overall. The legume DM yields used to calculate the BNF-N are based upon legume contents and therefore BNF-F followed the same pattern. Nitrogen from BNF represented 25% and 43% of N inputs to forage fields in 2009 and 2010, respectively. Forage fields had net surpluses of N in both years and a surplus of P in 2009. A net deficit of K was observed both years.

Table 3.15 Total N, P, K, and ammonium N concentrations of manure from PEI site in 2009 and 2010

	Semi-solid Dairy			**Dry Heifer**
	Spring	Summer	Fall	
2009				
N %	0.54	0.53[‡]	0.53	0.54
Ammonium-N %	0.20	0.19[‡]	0.18	0.067
P %	0.13	0.11[‡]	0.10	0.11
K %	0.29	0.27[‡]	0.25	0.28
2010				
N %	0.55	0.56	0.55[‡]	0.75
Ammonium-N %	0.20	0.13	0.18[‡]	0.12
P %	0.09	0.08	0.08[‡]	0.13
K %	0.31	0.41	0.34[‡]	0.40

[‡] No samples obtained for this period, values are averages of manure of the same type

Corn fields had surpluses of N and P both years and a surplus of K in 2010 (Table 3.16). The inputs of manure N and K to corn fields in 2010 were double those of 2009. Manure was applied in the spring in 2009, whereas in 2010, corn fields received manure in both the spring and after harvest in the fall. However, as a result of the lower concentrations of P in manure in 2010, P inputs did not increase as much in 2010 as manure N and K. Corn fields also received broadcast applications of diammonium phosphate prior to planting in each year. Silage corn yields were slightly higher per hectare in 2010 than in 2009. The corn fields had larger N and P surpluses than other crop groups and correspondingly low NUEs.

Table 3.16 Nutrient budget for corn fields at the PEI site in 2009 and 2010

	2009			2010		
Combined areas of all fields (ha)	13			15		
DM yield (t/ha)	12			14		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:	kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}		
Manure	185	43	99	381	60	220
Fertilizer	32	82	0	31	79	0
Atmospheric N deposition	5	0	0	5	0	0
Seed	< 1	< 1	< 1	< 1	< 1	< 1
Total inputs	**222**	**125**	**99**	**417**	**139**	**220**
Outputs:						
Crop off-take	112	27	112	145	31	142
Total managed outputs	**112**	**27**	**112**	**145**	**31**	**142**
Net Balance	110	98	-13	272	108	78
Nutrient use efficiency[‡]	**50%**	**22%**	**113%**	**35%**	**22%**	**65%**

[‡] Managed outputs / inputs (%)

The barley field group did not receive any manure applications either year; however, 17-17-17 and 20-22-10 fertilizer was applied in 2009 and 2010, respectively. The change in fertilizers brought inputs in 2010 closer to the crop requirements; however, P was still in surplus both years (Table 3.17). N and K were in deficit both years, though in 2010 the N deficit was close to zero.

Table 3.17 Nutrient budget for barley fields at the PEI site in 2009 and 2010

	2009			2010		
Combined areas of all fields (ha)	19			24		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:	kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}		
Fertilizer	29	29	29	58	63	29
Atmospheric N deposition	5	0	0	5	0	0
Seed	3	1	1	3	1	1
Total inputs	**37**	**30**	**30**	**66**	**64**	**30**
Outputs:						
Crop off-take	71	14	58	67	13	54
Total managed outputs	**71**	**14**	**58**	**67**	**13**	**54**
Net balance	-34	16	-28	-1	51	-24
Nutrient use efficiency[‡]	**192%**	**47%**	**193%**	**102%**	**20%**	**180%**

[‡]Managed outputs / inputs (%)

Table 3.18 Nutrient budget for the crop production component at the PEI site in 2009 and 2010

	2009			2010		
Combined areas of all fields (ha)	88			82		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:	kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}		
Manure	119	25	61	129	20	79
Fertilizer	11	18	6	22	33	9
Biological N fixation	32	0	0	50	0	0
Atmospheric N deposition	5	0	0	5	0	0
Seed	1	< 1	< 1	1	< 1	< 1
Total inputs	168	43	67	207	53	88
Outputs:						
Crop off-take	110	18	110	132	19	102
Total managed outputs	**110**	**18**	**110**	**132**	**19**	**102**
Net balance	58	25	-43	75	34	-14
Nutrient use efficiency[‡]	**65%**	**42%**	**164%**	**64%**	**36%**	**116%**

[‡]Managed outputs / inputs (%)

The different crop groups making up the CPC at the PEI site each had considerably different NUEs and nutrient balances. With the exception of the forage field groups in 2010, P was the only nutrient that consistently had surpluses in all crop groups. In stark contrast to fairly low contributions of N and K to the total inputs, 11 and 10%, respectively, the P from synthetic fertilizers accounted for 62% of P inputs across the entire CPC in 2010 (Table 3.18). The CPC had a net deficit of K both years which was larger in 2009 than in 2010. N inputs and outputs were all higher in 2010 than in 2009 resulting in a slightly larger surplus that year.

3.3.2.2 PEI Animal Production Component

The farm produced crops were the largest flows of N, P, and K into the APC and manure was the largest flow out of the APC (Table 3.19). Purchased feed supplements and barley were large inputs of N and P, contributing to approximately 30-40% of the total N and P inputs. The purchased feeds K did not contribute greatly to K inputs in the APC. Surpluses of N, and K were observed both years in the APC. P was also in surplus both years; however the 2009 surplus was close to zero.

Table 3.19 Nutrient budget for the animal production component at the PEI site in 2009 and 2010

	2009			**2010**		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:		kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}	
Off-farm feed supplements	66	9	10	65	11	9
Purchased barley	18	4	6	17	4	5
Bedding	3	2	6	3	2	9
Crops produced on-farm	110	18	110	132	19	102
Total inputs	**197**	**33**	**132**	**217**	**36**	**125**
Outputs:						
Milk	31	6	7	34	6	7
Animals	2	< 1	< 0.1	3	< 1	< 1
Manure spread on-farm	119	25	61	129	20	79
Total managed outputs	**152**	**31**	**68**	**166**	**26**	**86**
Net balance	45	2	64	51	10	39
Nutrient use efficiency[‡]	**77%**	**94%**	**52%**	**76%**	**72%**	**69%**

[‡] Managed outputs / inputs (%)

3.3.2.3 PEI Farmgate Whole Farm Nutrient Balance

Nutrient surpluses and associated low values of NUE were calculated for N, P, and K in both years at the farmgate level (Table 3.20). The NUEs and surpluses for N and K were fairly consistent from 2009 to 2010; however the P surplus was greater in 2010. As noted for the CPC, higher P inputs from synthetic fertilizer had considerable influence on the P balance at the farmgate level. Fertilizer was the largest P input, and accounted for 55 and 66% of total P inputs to the farm in 2009 and 2010, respectively. Purchased feed concentrates were the primary inputs of N and K. BNF-N followed purchased feed as the next largest source of N inputs.

Table 3.20 Farmgate whole farm nutrient budget at the PEI site in 2009 and 2010

	2009			**2010**		
	N	**P**	**K**	**N**	**P**	**K**
Inputs:		kg ha^{-1} yr^{-1}			kg ha^{-1} yr^{-1}	
Feed Concentrates	84	13	16	82	15	14
Bedding	3	2	6	3	2	9
Seed	1	< 1	< 1	1	< 1	< 1
Fertilizer	11	18	6	22	33	9
Biological N fixation	32	0	0	50	0	0
Atmospheric N deposition	5	0	0	5	0	0
Total Inputs	**136**	**33**	**28**	**163**	**50**	**32**
Outputs:						
Milk sales	31	6	7	34	6	7
Livestock sales	2	< 1	< 1	3	< 1	< 1
Total managed outputs	**33**	**6**	**7**	**37**	**6**	**7**
Net balance	103	27	21	126	44	25
Nutrient use efficiency ‡	**24%**	**18%**	**25%**	**23%**	**12%**	**22%**

‡Managed outputs / inputs (%)

3.3.2.4 PEI Soil test P and K concentrations

Of the field areas sampled at the PEI site, the proportion with soil test P concentrations rated as very high (>78 ppm) was greater in 2011 than the earlier soil test data from 2008 and 2009 (Table 3.21). However, the proportion of sampled field areas with soil test P concentrations rated as high (59 to 78 ppm) was greater in earlier years than in 2010 and 2011. The proportion of sampled field areas with soil test K concentrations rated as high (>112 ppm) was greater in 2010 and again in 2011 in comparison with the earlier years. The proportion rated as medium high (75 to 112 ppm) declined in 2010, but was greatest in 2011. The same fields were not sampled each year at the PEI site and relatively few samples were obtained for several years; therefore, it is difficult to conclude that the trends in soil test P and K concentrations reported in table 3.21 are representative of fields across the whole farm.

Table 3.21 Percent of sampled farm field area at the PEI site rated with low, medium, or high soil test P and K levels

	2008	2009	2010	2011
Total area (ha)	23	23	33	15
No. of fields sampled	4	3	6	3
Soil Test P[‡]				
Low (<20ppm)				
Medium (20-58 ppm)	46	45	77	30
High (59-78 ppm)	54	55	10	39
Very high (>78 ppm)			13	31
Soil test K[‡]				
Low (< 38 ppm)				
Medium (38-74 ppm)	39	45	77	
Medium high (75-112 ppm)	54	55	10	69
High (>112 ppm)	7		13	31

[‡] nutrient level categories from the NB Crop Fertilization Guide (Anonymous, 2001).

3.4 DISCUSSION

The NB and PEI farm sites in this study were not selected as contrasting dairy systems, but rather as farms which could be representative of dairies in Atlantic Canada. The two sites have very similar livestock densities close to 1.25 AU ha^{-1} and fewer than 100 cows in the milking herd. However, the PEI site is a slightly smaller scale operation than the NB site with fewer animals and a smaller land base used to grow crops. Milk productivity was slightly higher on a per cow basis at the PEI site. The cropping systems used at both sites were different; in NB forage was the predominant crop, while the PEI site had a rotation of forage, corn and barley. The main external inputs to each farm were also different. The NB site imported hog manure and complete feeds to supplement haylage, whereas the PEI site imported synthetic fertilizers and feed components to incorporate in TMR.

3.4.1 Farmgate WFNB and External Nutrient Flows

The range of farmgate NUEs reported in other WFNB studies (Table 3.1) was 14 to 48% for N. The 20-24% N-NUEs observed at the farm sites in this study were low relative to this range, but similar to the 17 to 25% range reported for other Canadian dairy N-NUE values (Paul and Beauchamp, 1995; Lynch et al., 2003; Roberts et al., 2008). WFNBs on other dairies have indicated that the main contributors to N inputs on dairy farms are feed imports and BNF (Powell et al., 2001; Spears et al., 2003a; Wattiaux et al., 2005; Roberts et al., 2008). Feed imports are also the main contributor to P imports (Anderson and Magdoff, 2000; Spears et al., 2003b). The results from the PEI site indicate the same major contributors to N inputs; however fertilizer was the largest contributor to P. The hog manure input at the NB farm is as much of a contributor to the inputs as feed and BNF.

Although P and K-NUEs may vary more from farm to farm, both farm sites had very low NUE values in comparison to other dairy WFNBs. The P and K NUE ranges from other WFNB studies (Table 3.1) were 19 to 635% and 18 to 151%, respectively. Kobayashi et al. (2010) was the only study which reported similar P and K-NUEs;

however, their nutrient surpluses were much greater than those observed at the NB and PEI sites, likely due to the high livestock density at their farm site. The observed farmgate P and K NUEs in PEI and NB are in stark contrast to studies which have investigated low input dairies where NUEs close to 100% have been cited (Weller and Bowling, 2004; Roberts et al., 2008).

Farms with the higher P and K-NUEs of over 100% typically produce all their own feed and often apply little to no fertilizer from off-farm sources. Dairies relying on more off-farm feed tend to have lower farmgate NUE; both the N (Roberts et al., 2008; Powell et al., 2010) and the P (Roberts et al., 2008; Weller and Bowling, 2004) NUEs are influenced by the amount of off-farm feed inputs used by farms. Livestock density can indicate the extent to which dairies rely on off-farm feed inputs in many cases. Farms with high AU ha^{-1} have less land per animal to produce feed, therefore rely more on feed inputs. Anderson and Magdoff (2004) found livestock densities and net P accumulation were related on dairies in Vermont and New York. Roberts et al. (2008) noted surpluses of N, P, and K increased with increasing livestock densities; however, all of the farms in their investigation were certified organic dairies with the highest animal density noted as 1.48 AU ha^{-1}.

The farmgate N surpluses observed across both sites and years of this study ranged from 102 to 159 kg N ha^{-1} yr^{-1} which is consistent with findings from relatively low livestock density dairies, see Table 3.1. However, the NB site had consistently lower N-NUEs and higher N surplus than the PEI site. The NB site had greater total N inputs and lower milk N outputs per hectare than the PEI site. N inputs from the imported hog manure accounted for approximately 30% of the total farmgate N inputs at the NB site; whereas the farmgate N inputs used for crop production at the PEI site represented only 8 and 13% of the total N inputs in 2009 and 2010, respectively. The fate of the surplus N was not assessed in the WFNBs; however, Hutson et al. (1998) predicted that volatilization and leaching accounted for 64% and 12% of excess N at a dairy in New York State, respectively. It is reasonable then to suggest that most of the observed excess N at the NB and PEI sites was lost to the environment.

In contrast to the results for N, milk P outputs were similar at both sites; however the PEI site had larger P inputs on a per hectare basis than the NB site. Farmgate inputs of P to the crop components at each site, hog manure at the NB site and fertilizer at the PEI site, contributed to the net P surpluses. The fertilizer P input at the PEI site was the greates external input of P to the farm. The farmgate P surpluses observed at the PEI site (27 and 44 kg P ha^{-1} yr^{-1}) were greater than those observed in NB and similar to the P surpluses observed among higher density (over 1.5 AU ha^{-1}) farms surveyed by Anderson and Magdoff (2000).

The farmgate NUEs at both sites were smaller than those observed in the CPC and APC. However, the inputs and managed outputs assessed for the CPC and APC include the largest flows of nutrient on the farm, manure from the dairy herd and farm produced crops. Consequently, when a nutrient surplus or deficit occurs within the APC or CPC, the associated NUE values are less sensitive to the nutrient imbalance due to the large amounts of nutrients in the overall inputs and managed outputs. The farmgate NUE values essentially incorporate the nutrient imbalances of both the CPC and APC and express them in terms of the efficiency with which the dairy farm produces its managed products.

3.4.1.1 Biological Nitrogen Fixation

At the farmgate level, BNF was a large contributor to N inputs at both sites. In 2009, inputs of BNF-N at the NB site were greater than feed or manure inputs. BNF-N fluctuated year to year; however, as a contributor to N inputs, at both sites it fell within the range of 24-37% of farmgate N inputs. Paul and Beauchamp (1995), Lynch et al. (2003), and Roberts et al. (2008) reported BNF accounted for 25, 52, and 59% of the total farmgate N inputs, respectively. The dairies investigated by Lynch et al (2003) and Roberts et al (2008) had somewhat similar CPCs, consisting of approximately 80 and 65% mixed forage, respectively, with the remaining land planted to small grains and corn. The research farm investigated by Paul and Beauchamp (1995) had less forage legumes, only 37% of the cropped land; however soybeans were also produced by the farm. WFNBs typically have reported BNF-N inputs to forages in ranges from 60 – 180 kg N ha^{-1}, depending on the legume content of the forage. Across entire CPCs, BNF-N inputs have wider reported ranges due to different cropping practices on-farms. The extent to which legumes are used within the CPC is clearly the most important determinant of BNF's importance as an input; however the methods used to quantify BNF also influence the estimates. It is also uncommon to find details of forage legume contents where mixed grass and legume forages are part of the CPC, despite the large influence this has on the ultimate BNF-N input.

The rhizodeposition factor in the Høgh-Jensen et al. (2004) model distinguishes the BNF estimates in this study; none of the WFNBs cited in Table 3.1 have incorporated such a factor in their assessments of BNF-N inputs. BNF-N accounted for by the rhizodeposition factor did influence the farmgate N balance. If the factor were excluded from the NB budget, the BNF-N inputs would be reduced by 21 and 12 kg N ha^{-1} in 2009 and 2010, respectively. This would represent an 11% and 7% decrease in total N inputs to the farm in 2009 and 2010, respectively. In PEI, slightly lower factors were used to correspond with the coarser soil textures than at the NB site. If the factor were excluded from the PEI budget, the BNF-N inputs would be reduced by 5 and 14 kg N ha^{-1} in 2009 and 2010 respectively. This would represent a 4% and 9% decrease in total N inputs to the farm in 2009 and 2010, respectively. The resultant farmgate N-NUEs would therefore increase by approximately one percent in PEI and two percent in NB. Considering that Høgh-Jensen and Schjoerring (2001) found amount of N from rhizodeposition could be greater than the N harvested above ground, the factors employed with the BNF-N models may be considered conservative.

Wattiaux et al (2005) had noted the influence that the method of BNF-N estimation can have on WFNBs. Their comparison of two WFNB spreadsheet programs, the Nebraska Nutrient Balancer which employed a BNF conversion factor and the Maryland Nutrient Balancer which used the N difference methods found large differences in estimated BNF-N inputs. The models used in this study are essentially a conversion factor applied to legume DM yields. The Nebraska Nutrient Balancer software which utilized BNF conversion factors excluded fields from BNF estimations if manure had been applied in the last two years. Such a criterion would have resulted in zero BNF-N inputs at both the NB and PEI site.

Table 3.22 Farmgate BNF inputs: comparison of BNF-N estimation methods

	NB		PEI	
	2009	2010	2009	2010
Adjusted Høgh-Jensen model	73	42	32	50
Adjusted Høgh-Jensen model without rhizodeposition factor	52	30	27	37
N balance method[‡]	32	44	29	51

[‡]BNF-N = total crop N off-take – (50% manure N + N deposition)

Employing the N balance method used by Lynch et al. (2003) with data collected from the NB and PEI sites resulted in very similar BNF-N estimates to those calculated with the adjusted Høgh-Jensen model including the additional rhizodeposition factor (Table 3.22). This provides some validation to the method of visually estimating forage legume contents and applying the adjusted Høgh-Jensen model. However, the methods do differ slightly in their responses to changes in agronomic conditions. At the NB site the two methods differed considerably in 2009; however, as noted in the following section, N off-take was low that year. Lower total N uptake from forage that year directly influences the N balance method, whereas the adjusted Høgh-Jensen model is influenced only by DM yields of the legumes, which were greater in 2009 than in 2010. It is interesting to note that excluding the rhizodeposition factor from the models results in smaller BNF-N estimates than from the N difference method. Presumably N that is introduced to the soil N pool via rhizodeposition will be available for uptake by the legumes and grasses. Without the rhizodeposition factor the models consider N off-take only for the legume, possibly ignoring some N which has been fixed, rhizodeposited, and subsequently taken up by grasses.

3.4.2 Nutrient Flows in Farm Crop Production Components

The N-NUE values found in the CPC on both farms is consistent with other system WFNB results on other dairy farms; studies cited in Table 3.2 have reported ranges of 53-89% for N-NUE of the overall CPC. Both sites were near the low end of this range in 2009 and 2010. Aarts et al. (2000) reported comparable N-NUEs for intensive commercial dairies in the Netherlands and similar to the NB site, 90% of the cropping area on these farms was forage. Although the NB site is less intensive in terms of livestock density than the farms surveyed by Aarts et al. (2000), the hog manure inputs in effect create a more intensive system with surpluses in the CPC near 100 kg N ha^{-1} yr^{-1}. Paul and Beauchamp (1995) found a similar N-NUE and slightly larger, 160 kg N ha^{-1} yr^{-1}, N surplus in the CPC of a dairy and beef operation in Ontario, Canada. The calculation of NUEs does contain inefficiency related to system limitations as well as wasted nutrients; however, if WFNB results from dairies with CPC N-NUEs near 89% represent optimal conditions, both the NB and PEI sites could improve their N management within the CPC.

There was a considerable difference in the 2009 and 2010 N off-take of NB forage fields. N off-take in 2009 was less despite greater DM yields that year. However, harvest times were not optimal and only two cuts of forage were harvested in 2009; whereas three cuts were harvested in 2010. In 2010 overall DM yield was less yet forage was harvested closer to the mid-flowering stage of alfalfa and consequently N content was higher in the total forage DM. The overall forage N concentration, determined by total N off-take divided by total DM yields, was 16 and 22 g kg^{-1} and in 2009 and 2010, respectively. Despite the variable output of N, the NB site had consistent N surplus across forage fields which make up the bulk of the CPC. Ammonium N accounted for approximately half of the N in the manure applied to forage in NB (See Table 3.7). If 50% of the ammonium was lost to volatilization, the N balance of the forage fields would still have surpluses of 88 and 45 kg N ha^{-1} in 2009 and 2010, respectively. Reducing the application rates of manure and adjusting manure application methods by lowering the splash plate to reduce N volatilization could likely improve the CPC N-NUE.

In contrast to the NB site where consistent NUEs were observed across most of the CPC area, the PEI site had specific areas where large variations in NUE occurred in the CPC, even if the overall CPC N-NUEs were similar at both sites. The PEI forage groups had slightly greater N-NUEs and lower surpluses than the NB site, possibly due to lower manure N inputs. In 2009, N-NUE was lower than in 2010; however several fields were harvested only once that year. Consequently, the N off-take was lower when averaged across all the fields. As the BNF input was calculated based on yield outputs from the CPC, it is likely an underestimate in 2009, as forage containing fixed N remained within the CPC at the end of the season. In 2010 the PEI site had the greatest BNF-N inputs observed in forage at either site, from the same forage fields that received the least manure N inputs. The 2010 forage in PEI also had the highest NUE observed in the study.

At the PEI site forage fields at the end of the rotation are plowed in the spring and planted to corn. These fields had the largest N inputs and lowest NUEs. Paul and Beauchamp (1995) also reported low N-NUE and a surplus of 207 kg N ha^{-1} for the corn portion of the CPC which received both fertilizer and manure inputs. The manure inputs alone at the PEI site would have resulted in N surplus on corn fields; however, synthetic fertilizer was applied, contributing more N to the surplus. The plowdown of the forage would also represent a source of N from within the CPC available to the corn fields. With the large amount of excess N present, the potential for loss to the surrounding environment would also be large. The PEI site has very well drained soils; therefore, it is likely that N is leaching into groundwater from the corn fields. In contrast to the corn fields, barley at the PEI site had very high N-NUE. PEI barley fields' N balance shifted from 2009 to 2010, largely due to a change in the fertilizer application rate. The N deficit observed in 2009 was almost completely balanced in 2010 by the change in fertilizer inputs.

The surpluses and P NUEs of the overall CPC in NB were similar to those reported by Bacon et al (1990) and Klausner et al. (1998); however, those observed by Kobayashi et al. (2010) were much greater. Slightly higher P and K concentrations in the total forage DM in 2009 coupled with higher yield resulted in greater outputs of P and K from NB forage fields than in the following year. The NB CPC had surpluses of 7 and 14 kg P ha^{-1} in 2009 and 2010, respectively. The manure P inputs in excess of the crop P uptake in 2009 were only 22% of the total inputs; however, in 2010, 40% of the manure P inputs were excess. The excess P in 2009 could be attributed to mitigating production risks, such as loss of available P to fixation. In 2010, crop uptake was less, despite a greater P input from manure, resulting in greater excess P than in 2009. Therefore, the additional P inputs from manure in 2010 could be considered as wasted rather than P applied to mitigate risk. Approximately one third of the manure P inputs to the CPC at the NB site were from imported hog manure; therefore, reducing the hog manure inputs could reduce the surplus P in the CPC and also reduce the farmgate inputs of P from an external source

The P-NUEs at the PEI site were below most other studies' values; however, Kobayashi et al. (2010) also observed low P-NUE in the field and surpluses in excess of 50 kg P ha^{-1}. Although the PEI forage had typical P-NUE, the barley and corn had very low values. The fertilizer P applied to barley fields was in excess of the crop uptake, particularly in 2010. The fertilizer P inputs in excess of the barley P uptake in 2009 were 53% of the total inputs and in 2010, 80% of the manure P inputs were excess. If the excess P in 2009 is attributed to mitigating production risks, then the additional 30 kg P ha^{-1} of fertilizer applied in 2010 was wasted, as the crop uptake was the same both years. Corn P uptake was slightly lower than the expected 56 kg P ha^{-1} uptake reported for similar silage corn yields in the region (APASCC, 1991). Similar to the N surplus in the corn fields, fertilizer and large volumes of manure contributed to P excesses near 100 kg P ha^{-1}. The fertilizer P inputs to corn fields alone were more than double the crop uptake both years. Matching fertilizer inputs to actual corn and barley requirements could clearly improve the efficiency of nutrient use at the PEI site.

Potassium was often in deficit among the crop groups at both sites resulting in high overall CPC K-NUE, a common finding in the few system WFNBs which have included K. In NB, the K field balance fluctuated from a deficit of -21 to a surplus of 26 the following year. Kobayashi et al (2010) and Bacon et al (1995) found similar balances close to zero in the CPC. The PEI site had a slightly larger deficit of K for the overall CPC. Farms with relatively low livestock densities such as the NB and PEI sites would not typically be at risk for high soil K concentrations and the associated ion imbalances in the dairy ration; however both site used external nutrient inputs containing K in addition to the farm produced manure. The predominance of K deficits observed in the CPCs and small proportion of the fields with high soil test K levels indicate that problems with excess K levels in the dairy ration are not likely under the farms' current management practices.

3.4.3 Nutrient Flows in Farm Animal Production Components

The surpluses observed in the APC at both sites were almost always lower than those of the CPC. Pathways for loss or accumulation of P and K in the APC are limited, particularly if manure stores are emptied of contents regularly as was the case at both farms. P and K NUEs in the APC are typically high, Klausner et al. (1998), Steinshamn et al. (2004), and Bacon et al (1990) all found high NUEs in the ranges of 76-91% for P and K. APC N-NUEs are typically slightly lower than P and K, but greater than the CPC N-NUE. The main loss of N in the APC is volatilization of ammonia during manure handling and storage; however, the greatest potential for volatilization losses occurs once the manure leaves the APC during application to fields (McGinn and Janzen, 1998). The APC N-NUEs at both sites were in the middle of the range of values (51-97%) from the WFNBs cited in Table 3.3.

Powell et al. (2002) and Lynch et al. (2003) indicate that lowering the content of P in dairy rations to NRC recommended levels can reduce the likelihood of P surpluses in the CPC of dairy farms. The NB and PEI sites differed considerably in their dairy rations. The NB site fed a diet of 0.48% P, greater than the highest National Academy of Sciences

National research Council (NRC) requirements for lactating dairy cows (NRC, 2001). The PEI site fed less P, typically 0.37%, which is near the high end of the NRC recommendations. The overall inputs of P to the NB APC were higher than in PEI, reflecting the higher P concentration in the lactation diet at that site. Dairy rations containing amounts of P above nutritional requirements considerably increases the amount of P found in manure (Morse et al, 1992). Neither farm balanced their dairy rations for P content. The ratio of N to P in dairy manure is typically lower than the ratio of N:P taken up by most plant tissues (Brady and Weil, 2008). Dairy manure with higher proportions of P with respect to N content due to imbalanced rations further exacerbates the existing challenge of matching crop requirements with nutrients from manure. An N:P ratio of 5:1 was typically observed in manure applied to fields at the NB site. The manure N:P ratio was close to that of crops from 2009; however, in 2010 the crops produced at the NB site had a greater ratio than the manure.

P and K NUEs fluctuated more from year to year than the N-NUEs. At the NB site, 2009 P and K NUEs were both lower than most other reported values, however the following year they increased. The increase in the 2010 P and K-NUEs to more typical levels suggest that there could have been an error in the accounting of P and K quantities in 2009. Manure accounts for most of the outputs from the APC; however, the sampling point for quantifying manure transfer from the APC to the CPC was immediately prior to application, at which point the manure from the NB dairy barn had already been combined with hog manure. The actual value of dairy manure outputs from the APC was obtained by subtracting the hog manure input. Therefore, differences in nutrient composition of the hog manure could have large effects on the input quantity at the scale that it was imported to the farm.

The PEI site had high P-NUE within the APC in 2009 which decreased in 2010. K-NUE had the opposite pattern in the APC. The fluctuations in the P and K APC balances in PEI were related to the manure composition which shifted over the course of the study. In 2009 P manure concentrations were higher, resulting in greater outputs from the APC and an essentially balanced P budget in comparison to the 10 kg P ha^{-1} yr^{-1}

surplus the following year. The manure K composition had the opposite trend with higher K content in 2010; therefore resulting in higher K outputs and lower surplus that year. The milk P outputs at both farms were similar in kg P ha^{-1} yr^{-1}.

Most P and K entering the APC leaves as manure, milk, or animals, leading to the high NUEs seen in most published WFNBs. However, both sites had years where there was considerable P and K surplus in the APC. At both the NB and PEI sites, heifer manure was not stored in a completely contained area; therefore, there was potential for nutrients to be lost as leachates from the piles. Whereas the NB dairy barn manure was contained in a lagoon, at the PEI site the dairy barn manure was stored in a covered shed with a sloping floor. If the shed contained high volumes of manure, straw bales were used to contain manure at the shed opening; therefore, there could also have been nutrient loss in leachates from these stores as well.

While the NB site results may have been influenced by error in quantifying the hog manure nutrient inputs, findings of surplus P and K in the APC have been reported elsewhere. Kobayashi et al. (2010) found P and K NUEs of 65 and 62% in the APC. The APC of their WFNB was split into separate feed storage, manure storage, and animal components. The primary source of the surplus P in the overall APC was the manure storage where 28 kg P ha^{-1} yr^{-1} was observed. Potassium surpluses of 52 and 93 kg K ha^{-1} yr^{-1} were found in both the feed storage and the manure storage areas, respectively. Kobayashi et al. (2010) attributed K lost in the APC to waste water from composting facilities and effluent from stored silage. The surpluses observed by Kobayashi et al. (2010) were much greater than those at the NB and PEI sites even though the P and K NUEs they cited were similar.

3.4.4 Comparison With WFNBs of Dairy Farms Without CPCs

The extent to which crop production was integrated with the whole farm at the NB and PEI sites was similar. Averaged across both years of the study, 65 and 60% of the feed N consumed by the dairy herds was produced by the CPC at the NB and PEI site, respectively. Dairies which rely entirely on imported feed and have no CPCs typically have greater NUEs than dairies which integrate crop and animal production (Table 3.23). The outputs used to calculate NUE, as defined in most WFNBs and in this study, are the managed nutrient outputs from the farm, including manure, composts, or crops. Dairies with no CPCs must export all their manure and as a result have greater total farmgate outputs.

The NUE of the integrated systems includes the losses of nutrients during manure storage through to its end use, the application to crops; whereas the NUE of the dairies without CPCs includes only the losses during manure storage. Manure exported from dairies without CPCs does not influence the efficiency of the dairy once it leaves the storages; however, further nutrient losses from the manure are transferred to another system where the manure is applied to land.

Table 3.23 Whole Farm N and P balances of dairy farms without crop components and the 2010 balances of the NB and PEI farm sites

	Dairy farms without crop components[1]		PEI site - 2010		NB site 2010	
	N	**P**	**N**	**P**	**N**	**P**
Inputs:	T yr^{-1}		T yr^{-1}		T yr^{-1}	
Feed	185.9	25.6	6.7	1.2	11.9	2.9
Bedding	2.0	0.4	0.3	0.2	0.1	< 0.1
Animals	1.7	0.5			< 0.1	< 0.1
Fertilizer /manure			1.9	2.7	8.0	1.9
Biological N fixation			4.1		6.8	
Atmospheric N deposition			0.4		0.8	
Seed			< 0.1	< 0.1	< 0.1	< 0.1
Total Inputs	**189.7**	**26.5**	**13.4**	**4.1**	**27.6**	**4.8**
Outputs:						
Milk + livestock sales	42.8	8.8	3.0	0.5	5.1	0.9
Manure	32.1	10.6			0.4	0.1
Total managed outputs	**74.9**	**19.4**	**3**	**0.5**	**5.5**	**1**
Net balance	114.8	7.1	10.4	3.6	22.1	3.8
Nutrient use efficiency [2]	**39.5%**	**73.4%**	**22.4%**[3]	**12.1%**	**20.0%**	**20.8%**[3]
NUE of livestock products[4]	**22.6%**	**33.2%**	**22.4%**	**12.1%**	**18.5%**	**18.8%**

[1] Spears et al. 2003a,b – 18 dairies from Utah and Idaho, mean milk herd size was 700 cows

[2] Managed outputs / inputs (%)

[3] Different from reported values in Tables 3.12 and 3.20 due to rounding

[4] (Milk + livestock sales)/ inputs (%)

The dairies without CPCs surveyed by Spears et al. (2003a) and the integrated dairies from this study have similar N-NUE when NUE is calculated with only the marketable livestock products (milk and livestock) as outputs. This adjusted version of N-NUE shows that the integrated systems are able to produce marketable products with comparable N-NUE to dairies without CPCs while also providing the service of recycling manure nutrients back into the system. The P-NUE of dairies without CPCs calculated with only livestock products as outputs remains greater than that of the integrated dairies in this study. However, dairies without CPCs have no P inputs for crop production and do not incur any losses of P to P accumulation in the soil.

3.4.4 Certainty in WFNB Results

Oenema et al. (2003) identified three classes of items in WFNBs with respect to their uncertainty. The first class was items such as inputs of conventional fertilizer which can be quantified with reasonable certainty through farmer financial or application records and fertilizer nutrient analysis. However, materials without measured quantities or known analyses are more difficult to quantify. Inputs such as manure and harvested crop outputs in the CPC were the next class, having uncertainties of 5-20% in their WFNB quantification. Items with uncertainties greater than 20% in their estimation were the last class and included BNF inputs and losses of nutrients through volatilization, leaching, denitrification, or runoff. Whereas uncertainty in the second class of items is often related to their spatial and temporal variability within the system, the last class of items with the greatest uncertainty was related to a lack of knowledge or data to properly quantify the nutrient flows.

When reported in published WFNBs, quantitative variation in nutrient flows is typically the variation of the mean of several years rather than the variation within the actual measures of each nutrient flow. With many components to each WFNB, and different methods involving combinations of estimates and measured nutrient flows, determining a quantitative measure of certainty in a final WFNB can be challenging.

Table 3.24 presents several quantitative assessments of the variation in items used in the WFNBs. The methods used to determine forage nutrient uptake relied on much smaller sampling units than corn sampling. The quadrats used in forage sampling captured a specific yield and nutrient composition associated with 0.5m^2 from which total uptake was calculated; whereas the total yield of corn silage was measured in loads and associated to the total field area. As a comparison, each corn silage load was the equivalent to a sample from roughly 1400 m^2. The quadrat sampling was much more sensitive to spatial variation within each field, resulting in a standard error of 8.7% of the mean total yearly N uptake measure for the field shown in Table 3.24. In contrast, the standard error represented only 4.5% of the mean P per load of corn silage.

Table 3.24 Variation associated with nutrient budget measures and estimates

Loads of corn silage		**Forage quadrat samples**	
n	5	n	4
DM (kg load^{-1})	2046 (72) ‡	1st cut uptake (kg N ha^{-1})	74 (12)
P (g kg^{-1})	2.1 (0.1)	2nd cut uptake (kg N ha^{-1})	63 (2)
kg P load^{-1}	4.4 (0.2)	total uptake (kg N ha^{-1})	137 (12)

Legume fixed N estimate (single cut)	
n	4
%Alfalfa	31 (8)
DM yield (kg ha^{-1})	3679 (225)
alfalfa DM (kg ha^{-1})	1150 (312)
kg BNF-N ha^{-1}	39 (11)

‡values are mean (standard error)

The primary focus of Chapter 2 was to determine if models could accurately predict the amount of BNF in mixed legume/grass forage fields within our geographic region. Models were selected and slightly adjusted to predict BNF-N with reasonable certainty based upon DM yields of alfalfa and red clover. Ultimately, the purpose of this work was to incorporate the models into the WFNBs to improve our certainty in the BNF-N inputs. However, the BNF-N input is dependent on our certainty in the DM yield of legumes. Legume DM yield was determined for each quadrat by visual estimates of the sward contents. The quantitative variation associated with the legume DM yields and the resultant estimates for BNF-N are shown in Table 3.24. Similar to the forage uptake measures, spatial variation led to large standard errors for yields, legume contents, and ultimately the legume DM yield.

The variation between quadrats related to spatial differences in forage fields that is shown in Table 3.24 is not the only uncertainty in the legume DM yield measures. Visual estimates were used to assess the legume composition of each quadrat before harvest. The actual legume contents of quadrats from two fields at each site were determined from sorting for the experiments in Chapter 2. The deviations of the visual estimates from the actual legume contents, on a DM basis, for each estimator involved in the study are shown in Table 3.25. With the exception of Estimator 3, mean alfalfa and red clover estimates deviated from the actual DM legume contents of the quadrats by approximately ten percentage points. Estimators 1 and 2, who accounted for the majority of the estimates, did not have consistent positive or negative bias; therefore, the estimates were not calibrated according to the legume DM content data.

Table 3.25 Deviation of visual estimates from actual forage legume contents

	Absolute deviation (%)		n	
	Alfalfa	Red Clover	Alfalfa	Red Clover
Estimator 1	10.9 (0.9)	8.9 (1.3)	130	49
Estimator 2	12.7 (1.3)	13.8 (2.9)	63	27
Estimator 3	25.2 (4.7)	-	15	-
Estimator 4	10.6 (2.1)	9.0 (2.3)	11	11
All estimates	12.4 (0.7)	10 (1.2)		

values are mean (standard error)
n = number of quadrat estimates verified by botanical separations

The influence of the legume content visual estimates on the CPC and the farmgate WFNB are shown in Table 3.25. Based upon the mean deviations from legume estimates in Table 3.25, the range between the +10% and -10% scenarios in Table 3.26 represent the uncertainty that was likely introduced to the budgets from the visual legume content estimates. Farmgate N-NUEs were shifted by approximately two percent for each increase or decrease of the quadrat legume legume content estimates by ten percentage points. The CPC was more drastically affected as BNF-N is a greater contributor to N inputs at the field level than at the farmgate. However, at the farmgate level, a change of 20 to 40 kg N ha^{-1} yr^{-1} is a considerable adjustment to N inputs.

Table 3.26 Sensitivity of 2010 whole farm nutrient budgets to visual estimates of forage legume content

	Adjustment to legume content estimate				
	+20%	**+10%**	**0**	**-10%**‡	**-20%**‡
NB					
Total BNF input kg (N ha^{-1} yr^{-1})	84	63	42	29	20
Crop Production Component					
N Surplus (N ha^{-1} yr^{-1})	124	103	82	69	60
Nitrogen Use Efficiency (%)	53%	57%	63%	67%	70%
Farmgate WFNB					
N Surplus (N ha^{-1} yr^{-1})	179	158	137	124	115
Nitrogen Use Efficiency (%)	16%	18%	20%	22%	23%
PEI					
Total BNF input (N ha^{-1} yr^{-1})	96	73	50	32	22
Crop Production Component					
N Surplus(N ha^{-1} yr^{-1})	120	97	74	56	46
Nitrogen Use Efficiency (%)	52%	58%	64%	69%	73%
Farmgate WFNB					
N Surplus (N ha^{-1} yr^{-1})	172	149	126	109	99
Nitrogen Use Efficiency (%)	18%	20%	23%	23%	25%

‡ quadrat estimates were not adjusted below zero

The noted quantitative variation within the nutrient flows on the farms seems consistent with the categorization of WFNB items based on uncertainty by Oenema et al. (2003). Spatial differences in crop yields and uptakes introduce variation to the measures used to quantify nutrient flows; however, there is a difference between finding heterogeneity at the individual field level and uncertainty in the actual total flow of nutrients at the farm level. Heterogeneity is a part of the system and variation from it should not necessarily be entirely translated as uncertainty. In most cases, quantitatively assessing the certainty in total nutrient flows at the farmgate or even CPC and APC level is challenging. Due to the large amount of data collected with respect to

BNF-N inputs, a quantitative assessment of the certainty of some aspects of this measure was possible.

There were instances for each nutrient budget where uncertainty was identified on a qualitative basis. At the NB site, hog manure was combined with dairy manure in the lagoon prior to field application. Physically this was an input to the APC, however the model of the dairy system used in the WFNB considered this an input to the CPC. Separating the nutrients from manure outputs from the APC into nutrients actually derived from the APC and those from the hog manure input was a challenge. Only one hog manure sample was obtained each year; however, the nutrient composition of manure in each load was likely not constant.

At both sites, the APC inputs from farm produced feed were shifted from 'as fed' during the 12 month budget period to the amounts produced from the CPC due to data limitations. There was a lag of approximately 6 months between when crops are actually produced as an output from the CPC and when they become an input of feed to the APC. The farm produced crops at both sites represent the largest inputs of N, P, and K to the APC, therefore this adjustment adds some uncertainty to the cycling of nutrients within the APC, as the nutrient outputs from a given year were actually produced with crop inputs from a different time period.

3.5 CONCLUSIONS

The farmgate WFNBs revealed similar NUEs and nutrient surpluses at both sites. The findings with respect to N coincide with other dairy WFNBs in the literature. N surpluses near 130 kg N ha^{-1} in this study were consistent with dairies which had a relatively low N-NUE but also maintain a low livestock density. Surplus N was found in both the APC and CPC; however, at both sites a greater portion of the overall N surplus occurred in the CPC. The models chosen for quantification of BNF-N inputs in Chapter 2 showed that BNF-N was a significant contributor to farmgate N inputs, typically representing near 30% of N inputs. This BNF figure is lower than other studies where forage represents a similar proportion of the dairy ration to the NB and PEI sites. The visual estimations of sward legume contents had a significant influence on the WFNB results as the estimated BNF-N quantities were very sensitive to legume content of the forage.

Low P and K NUEs and high surpluses at the farmgate level revealed that there were some challenges managing these nutrients. The NB site had small surpluses of P across most fields in the CPC; however, there were also considerable surpluses of P and K in the APC. The surplus of P and K in the APC at both sites was one of the most uncertain areas of the WFNBs. The surplus P and K was assumed to be lost through leachate in the APC; however, the exact quantities lost are uncertain as there were challenges quantifying the ‘as fed’ inputs to the APC and in subtracting the hog manure from APC outputs at the NB site. The PEI site was more heterogeneous with large surpluses found only in the corn and barley fields of the CPC rotation. At the NB site dairy rations had higher P contents than is typically recommended by nutritionists and other WFNB work (Powell et al., 2002) has shown small reductions in excess ration P can drastically influence P outputs from the APC.

At both sites imported manure (in NB) and fertilizers (in PEI) contributed to inputs that were higher than crop requirements in the CPC. These inputs are both from external sources and therefore have considerable influence on the farmgate NUEs. At the PEI site the CPC and farmgate P-NUE could be greatly improved by matching the fertilizer inputs to the corn and barley crop requirements. At the NB site reducing the volumes of imported hog manure could decrease the surpluses of N and P observed in the CPC and improve the farmgate NUE. However, the concentration of P in the purchased dairy ration was also well above that recommended by the NRC. Purchased feed was the largest source of P inputs to the NB site; therefore, re-formulating rations with less P content could also be and effective means of improving P-NUE.

The field by field approach used in this study to quantify nutrient flows in the CPC provided a large amount of data for analysis; however, it may not be ultimately necessary for the development of a useful system WFNB for farmers. Certainly, no farmer or nutrient management planner would invest the time this method requires in order to prepare their own WFNB. For the purposes of evaluating a method for estimating BNF-N inputs at both sites, quadrat sampling and visual estimates proved effective. However the detailed N, P, and K uptake data provided by multiple quadrats clipped from each field at each harvest could likely be approximated with several composite forage samples taken at each cut. Both farms participating in this study maintained some form of records for forage yields, as loads of silage or numbers of bales, which could substitute for yield data obtained from quadrats. While reducing the emphasis on a field by field approach is warranted, the results from the PEI site indicate that there is merit in maintaining distinct sub-components within the CPC for different crops.

At both sites, external inputs to the CPC contributed to surpluses of N and P within the CPC; however, a traditional field nutrient management plan could likely have provided similar findings. However, the WFNB does provide some context for how surpluses in the CPC ultimately influence the efficiency with which the dairies produce marketable products from the APC. Additionally, the NB site WFNB showed some opportunity for managing surplus P in the CPC through adjustments to the dairy ration, which would not be considered with field nutrient management.

CHAPTER 4 CONCLUSIONS

4.1 ASSESSMENT OF FORAGE LEGUME BNF-N

The $\delta^{15}N$ method was an effective means of determining BNF-N from the commercial farm sites. The adjusted Høgh-Jensen et al. (2004) model was the most reliable DM conversion model for estimating BNF-N from red clover and alfalfa. Slight adjustments based upon the measured mean %Ndfa of red clover (77%) and alfalfa (72%) were made to the model parameters to obtain the closest BNF-N estimates for use in the WFNBs. Rhizodeposition factors suggested by Høgh-Jensen et al. (2004) were included in the models when estimating BNF-N in the WFNBs. These factors had a considerable effect on the overall N inputs and farmgate N-NUE at both farm sites. The BNF values obtained from the adjusted Høgh-Jensen et al. (2004) model with the rhizodeposition factor generally agreed with BNF estimates derived by the balance method in the CPC N flows. Perhaps as influential as the inclusion of the rhizodeposition factors was the influence that visual estimates of forage legume contents had on BNF-N. Although the primary focuses in Chapter 2 were determining proportions of N derived from BNF and the ability of models to predict this in forage legumes in Atlantic Canada, the simple field observations of legume content in mixed legume/grass forages proved to be an important consideration for quantifying BNF-N inputs.

4.2 WHOLE FARM NUTRIENT BUDGETS

The WFNBs for the NB and PEI sites reveal a similar picture at the farmgate level, with slightly greater P and K surpluses at the PEI site. Both farms imported feed as well as nutrient inputs for crop production resulting in relatively low farmgate NUEs. However, the internal flows of nutrients were different between the two sites, primarily due to the different crop rotations. Whereas forage was predominant in the crop rotation in NB, resulting in more consistent nutrient balances and NUEs in the CPC, the corn-barley-forage rotation at the PEI site had large variations in the nutrient balances and NUEs for each phase in the rotation. Despite the differences in the CPCs, the budgets of the overall CPC were similar with respect to N and K. The PEI site had smaller CPC P-NUEs and large P surpluses related to high fertilizer rates applied to corn and barley. The separation of the CPC into distinct crop groups is therefore a useful practice for interpreting the WFNBs.

At both sites the APCs had surplus P and K. These surpluses could have been lost to the environment from manure or silage stores; however, the magnitude of the surpluses at the PEI site suggest that there may be some uncertainties in this portion of the WFNB. N surpluses were noted in both the APC and CPC; however, at both sites a greater portion of the overall N surplus occurred in the CPC. Likely, the most effective means of improving farmgate NUEs at both sites would be to focus on the CPC. At the PEI site this could be accomplished by matching fertilizer and manure inputs to crop requirements. At the NB site, adjusting manure application equipment to minimize N losses through volatilization could improve N-NUE. Lowering the dairy ration P content could also help improve P-NUE in the CPC by reducing P manure outputs from the APC; however a reduction in the volume of imported hog manure would likely be the simplest way to improve NUE of N, P, and K.

4.3 RECOMMENDATIONS

The adjusted Høgh-Jensen et al. (2004) model proved effective at quantifying BNF-N from legume DM yields. The red clover model for determining BNF-N employed in the PEI WFNB was based upon %Ndfa values obtained from only two fields in PEI; therefore, it may be worthwhile to incorporate some values from red clover grown in other regions in Atlantic Canada to ensure it can be applied with confidence in the other Maritime Provinces. The last step in ultimately determining the contribution of BNF-N to dairy farm N inputs is effectively determining the legume DM yields. The visual estimates of forage legume contents from quadrat sampling were reasonably accurate, particularly if estimators were able to participate in sorting the contents of a quadrat after harvest to determine the actual legume contents. Environmental club coordinators in NB who offer nutrient management planning services across the province participated in the project and were supportive of a more defined method for determining forage legume contents. Incorporating similar exercises for estimating forage legume contents in nutrient management planner training in the region could allow us to obtain better valuation of the importance of BNF-N to dairy farms in Atlantic Canada.

The rhizodeposition factor incorporated with the Høgh-Jensen et al. (2004) models was a conservative estimate based on initial work by Høgh-Jensen and Schjoerring (2001), who indicated that rhizodeposited BNF-N could be as large as that in the harvested biomass. Further work to determine actual quantities of BNF-N inputs to mixed grass and legume forages from rhizodeposition is warranted as it could potentially dramatically increase the understanding of the contribution of BNF-N to farm N inputs.

The findings of the WFNBs reinforce the importance of internal nutrient cycling between the crop and animal components for overall dairy farm productivity. Within the APC at both sites manure N outputs were three times the milk outputs, and on-farm produced crops were roughly twice the N inputs from purchased feeds. Though milk is ultimately the saleable product from dairies, the WFNB allows farmers to gain some perspective as to the true value in farm products such as manure and their crops. The WFNBs also highlight BNF's importance as an N input to dairy farms. As a management tool to increase farm NUE the WFNBs compiled for the farm sites in this study may not greatly improve upon traditional nutrient management plans. The surplus N and P observed in the CPC at each site would be quickly evident in field nutrient management plans. However, at present in Atlantic Canada the onus for reducing nutrient imbalances and mitigating environmental risks such as P accumulation in soils is on farmers themselves. Relating inefficiencies in the CPC to the actual NUEs of the whole farm is a useful aspect of WFNBs in encouraging farmers to adopt better management practices.

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