BABCOCK INSTITUTE DISCUSSION PAPER
NO. 2007-4

NUTRIENT MANAGEMENT APPROACHES AND TOOLS FOR DAIRY FARMS IN AUSTRALIA AND THE U.S.

Cameron J.P. Gourley
Department of Primary Industries Victoria,
Ellinbank Center, 1301 Hazeldean Rd,
Ellinbank, Victoria 3821, Australia

J. Mark Powell
USDA–ARS US Dairy Forage Research Center
1925 Linden Drive West,
Madison Wisconsin 53706, USA

The Babcock Institute for International Dairy Research and Development
University of Wisconsin-Madison, College of Agricultural and Life Sciences
240 Agriculture Hall, 1450 Linden Drive
Madison, WI 53706-1562 USA

The Babcock Institute offers continuing opportunities for sponsorship of our market and trade analysis, international dairy research, international market development activities and educational materials, including our website. If you are interested in discussing these opportunities, please call Karen Nielsen at 608-265-4169.

The Babcock Institute for International Dairy Research and Development
is a joint program of the
University of Wisconsin-Madison College of Agricultural and Life Sciences
University of Wisconsin-Madison School of Veterinary Medicine
University of Wisconsin Extension Cooperative Extension Division

Funding for this study was provided by CSREES USDA Special Grant 2006-34266-17274

ISBN 978-1-59215-105-1

The Babcock Institute
College of Agricultural and Life Sciences
240 Agriculture Hall, 1450 Linden Drive
Madison, WI 53706-1562

Phone: 608-265-4169; Fax: 608-262-8852
Email: babcock@cals.wisc.edu
Internet: http://babcock.cals.wisc.edu

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

Financial support for this project came from the Department of Primary Industries Victoria, USDA - ARS US Dairy Forage Research Center, Dairy Australia, and The Babcock Institute for International Dairy Research and Development, University of Wisconsin-Madison through the USDA-CSREES Special Grant 2006-34266-17274.

NUTRIENT MANAGEMENT APPROACHES AND TOOLS FOR DAIRY FARMS IN AUSTRALIA AND THE U.S.

Cameron J.P. Gourley and J. Mark Powell

EXECUTIVE SUMMARY

Dairy operations in Australia, the U.S., and other industrialised nations, continue to intensify. In general, farm numbers are declining, while milk production per cow and the reliance on imported feed, are increasing. Nutrient surpluses on many dairy farms are a problem in Australia and the U.S. and pose an increasing threat to the greater environment. Nutrient management tools can assist dairy farmers to remain profitable and meet increasing demands for improved environmental standards.

While the major nutrient imports onto dairy farms (i.e. fertilizer and feed) and exports (i.e. milk and animals) are generally the same for confinement-based and grazing-based dairy operations, within-farm nutrient cycling processes may be quite different. In confinement-based dairy operations, farmers generally manage mixed animal and cropping operations, and have more control on cow diets, which in turn influences the quantity and nutrient concentration of manure, and the capture, storage and land application of excreted manure. In grazing-based dairy operations, farmers manage grazed pastures, and although they purchase feed, they generally have less control of dairy cow diets, with feed quality and nutrient content varying throughout the year. Additionally the redistribution of manure nutrients in the landscape is largely from direct deposition by animals. Manure deposition is often uneven, with high nutrient loads in some areas which may pose a high risk of nutrient loss and environmental contamination.

In Australia, the U.S., and internationally, there are many nutrient management tools available to dairy farmers, advisors and researchers. Generally, these nutrient management planning tools, either in part or as a whole, attempt to quantify nutrient imports and exports at the farm scale, nutrient flows and use efficiencies at the component scale (i.e. feed, milk, manure land-application, plant uptake) and soil fertility status and nutrient loss at the field or paddock scale. These tools may vary in terms of their objectives, approaches, and degrees of complexity, and have different inputs and data requirements, algorithms used in calculations, and how integrated outcomes are presented to the end user.

There is further scope to improve nutrient management tools, so that they not only quantify nutrient balances on dairy farms, but also assist in identifying opportunities for enhanced nutrient use within farm components, and reduced nutrient losses. Future developments in nutrient management tools should strive to achieve greater uniformity in inputs and methodologies, develop more efficient ways to gather on-farm data, assess and present uncertainties in estimated nutrient balances and efficiencies, develop improved nutrient balance and efficiency targets and interpretation, and link nutrient management recommendations with farm profitability and environmental outcomes.

INTRODUCTION

As in many parts of the industrialized world, the dairy industries in Australia and the U.S. continue to intensify. In both countries, the number of dairy farms has declined significantly over the past 25 years while average farm herd sizes and annual milk production per cow have increased. Projected trends are for fewer and larger dairy farms with further increases in milk production per cow. Future dairy farms will use more imported feed and fertilizer, grow more monoculture crops, and utilize more marginal soils.

Dairy operations can contribute significant amounts of nitrogen (N) and phosphorus (P) to water and air. Blue-green algal blooms have become a regular feature of water storage and river systems in Australia, and agriculture is recognized as a significant contributor to these increased nutrient loads [11, 88, 46]. The U.S. Environmental Protection Agency identified agriculture as the major source of causative nutrients in 50% of the lakes and 60% of the river lengths determined to have impaired water quality in the U.S. [125]. Nitrogen and P losses from dairy farms in the Midwest are thought to be major contributors to the N and P loading of regional and national water bodies, such as the Mississippi River and the Gulf of Mexico.

Environmental risks associated with livestock production can be attributed to high stocking rates, inefficiencies in nutrient use, and an imbalance between on-farm nutrient imports and exports, which may lead to the accumulation and loss of nutrients from parts of the landscape [129, 109]. Soil nutrient build-up, losses and risks of environmental contamination increase when nutrient imports onto a farm (e.g., in the forms of feed, fertilizer, N fixation by legumes) exceed the amount of nutrients leaving the farm in products (e.g., in the forms of milk, animals, crops, hay). These nutrient surpluses tend to increase as farms intensify and stocking rates increase.

Where N has been land-applied as manure, fertilizer or deposited directly by grazing livestock as dung and urine, losses of N may occur via nitrate leaching, which pollute surface and ground water, ammonia (NH_3) gas, which upon redeposition causes acidification and eutrophication of surface waters, and as potent greenhouse gas nitrous oxide (N_2O). Excess P on dairy farms can increase soil P levels beyond agronomic requirements, which increases the risks of P losses via soil surface runoff or via leaching in sandy soils. Efforts to reduce N and P losses from dairy farms should include strategies that reduce N and P imports, as well as practices that reduce N and P losses [114]. These nutrient management challenges are faced not only by the Australian and U.S. dairy industries, but by animal agriculture in most industrialized countries [120].

Over the past 15 years or so, governments and industries in Australia and the U.S. have invested in strategies aimed at improving the environmental performance of livestock farms. Research and development efforts have focused on identifying opportunities for enhanced nutrient use within the animal-feed-manure-soil/crop components of livestock farms. Particular emphasis has been directed towards large-scale farms, due to greater nutrient use, manure production, and potential for nutrient accumulation and losses.

The intensification of animal agriculture in Australia and the U.S. has increased societal pressure on farming communities to reduce nutrient losses to water and air. Livestock producers are increasingly required to provide evidence that farm practices are meeting environmental standards. Nutrient management tools can assist producers to meet both production and environmental goals by identifying opportunities for improving nutrient use, decreasing on-farm nutrient surplus, and accumulation thereby reducing risks of off-farm nutrient losses and environmental contamination.

The purpose of this technical paper is to:

- outline on-going structural changes in the Australian and U.S. dairy industries and the implications for nutrient use, accumulation, losses, and environmental contamination;
- describe the major nutrient flow pathways, pools, and transformations on confinement and grazing-based dairy operations;
- outline different approaches and scales of on-farm nutrient management planning;
- provide examples of nutrient management planning tools and their applications; and
- suggest changes to nutrient management planning tools that enhance their use and benefits to dairy producers and the broader environment.

STRUCTURAL CHANGES WITHIN THE AUSTRALIAN AND U.S. DAIRY INDUSTRIES

Significant structural changes continue to occur in the international dairy industry. In 2006, around 500 million tons of milk were produced on dairy farms in the industrialized world, and while total cow numbers have remained fairly constant, milk production per cow continues to increase [37]. In general, farm numbers are declining while herd size and stocking rates (animal units/ha) are increasing. Dairy farms are becoming more specialized in parts of the operation, such as feeding and growing fodder, and there is greater reliance on purchased inputs such as fertilizer, forage and grain, and dietary mineral supplements. These structural changes have occurred across the continuum of lower input grazing-based operations, which dominate the Australian dairy industry and higher input confinement-based operations, which dominate the U.S. dairy industry.

The Australian Dairy Industry

While Australia produces only about 2% of the world's annual milk production, it is the third largest milk exporter, after Europe and New Zealand, and is one of the most efficient milk producers on a cost per volume basis [72]. Along with most other dairy producing countries, the Australian dairy industry continues to undergo significant change. The number of dairy farms has substantially declined over the past twenty-five years (Table 1). There has been a greater proportional decline in farm numbers in less favorable environments, with a consolidation around irrigation and higher rainfall regions. For example, dairy farm numbers in Western Australia and Queensland have reduced by more than 60% over the past 15 years whereas in Victoria, the decline has only been around 30% [6].

As farm numbers have declined in Australia, the average dairy herd size has increased from 86 cows per farm in 1980 to more than 210 in 2005, totaling around 2.1 million cows nationally. Average annual production per cow has increased from 2,850 L to 5,163 L, over the same period, and the national milk production in 2005 was around 10 billion L, a slight reduction from its historic peak in 2002 (Figure 1).

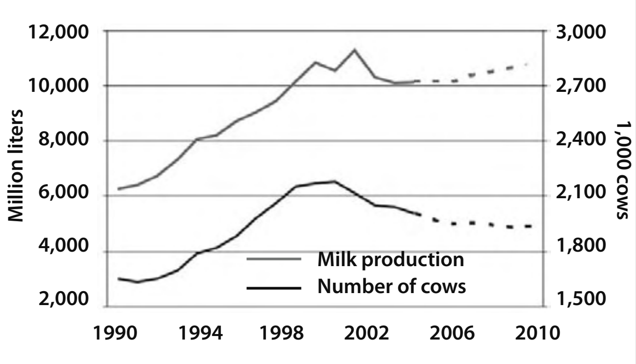
TABLE 1. Key statistics and changes in the Australian dairy industry, 1980 to 2005.

	Year		%
Farm statistics	**1980/01[1]**	**2004/5[2]**	**Change**
National scale			
Number of farms	22,000	10,112	–55%
National dairy herd size (M)	1.9	2.1	+10%
Farm scale averages			
Farm milking area (ha)	64.6	113.9	+75%
Milk yield (L/cow/yr)	2,850	5,163	+76%
Stocking rate (cows/ha)	1.33	1.82	+37%
Imported grain/ concentrates (t/farm)	25.4	210.2	+710%
Silage cut (t/farm)	43.6	171.5	+388%
Hay (t/farm)	66.9	151.5	+125%

Source: [1]ABARE, [7], [2]ABARE, [6].

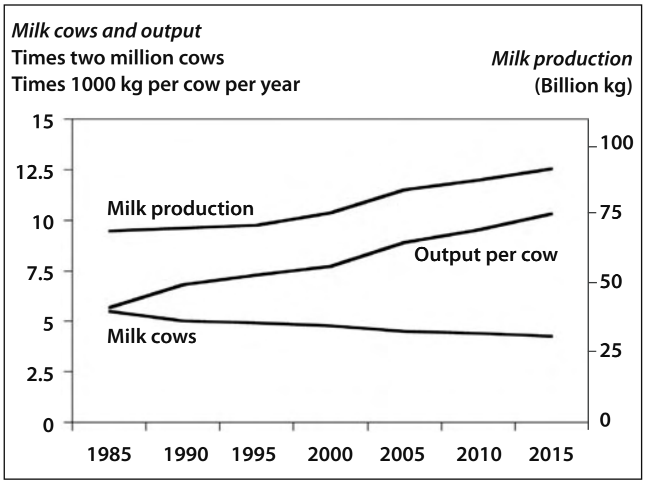
Despite the grazing-based nature of the Australian dairy industry, a key driver of the increased per cow productivity in Australia over the past twenty-five years has been the increase in supplementary feeding [31, 6]. In 1980, most dairy farms were totally reliant on "home-grown" pasture and conserved forage. In 2004/05, 91% of all dairy farms used imported concentrates or grain, with the average dairy farm feeding supplements at approximately 1.1 ton/cow/year, mostly barley or wheat. The other major supplement

FIGURE 1. Actual (solid line) and projected (dashed line) Australian national milk production and cow numbers, 1990–2010.



Source: ABARE, [6].

FIGURE 2. Trends in the U.S. dairy industry.



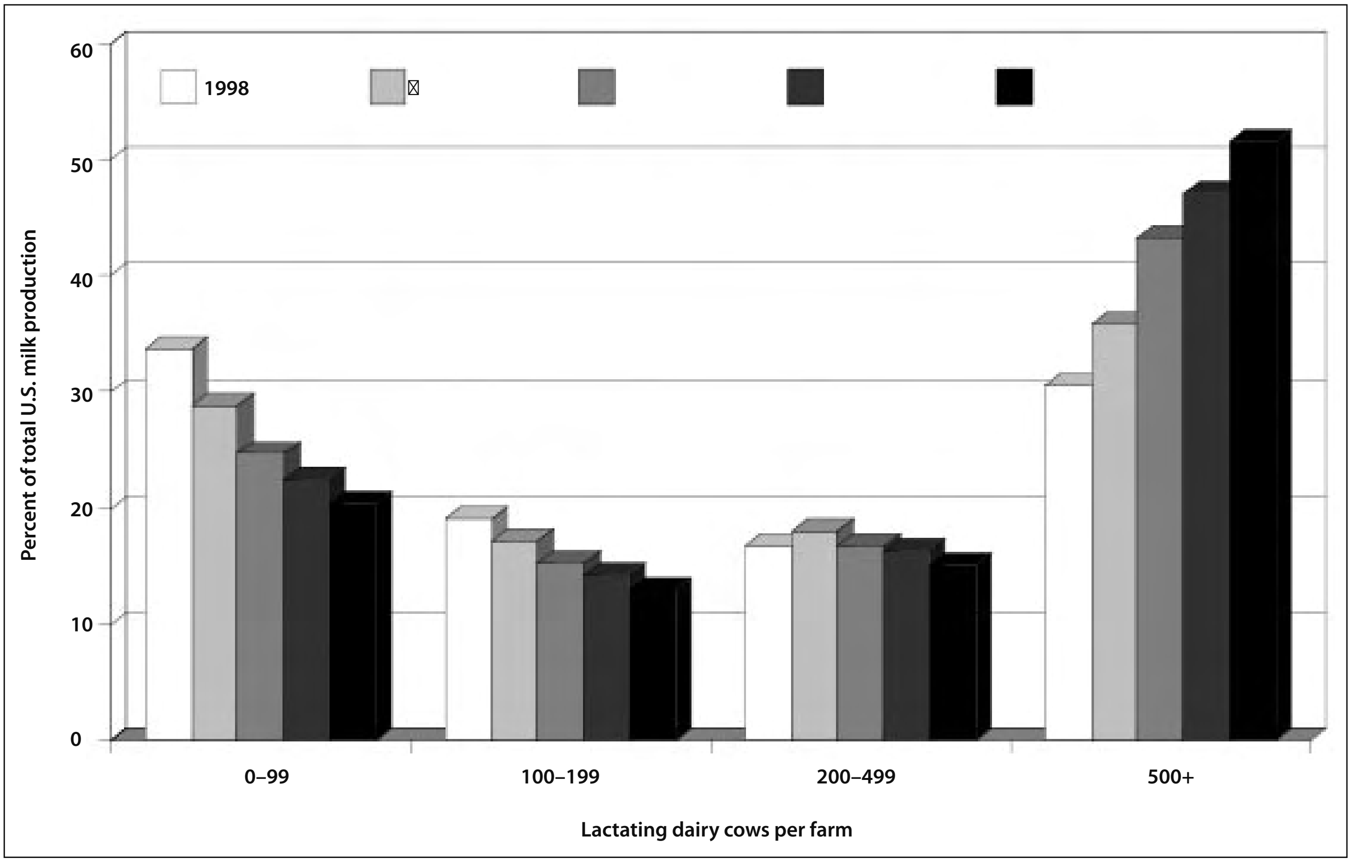
brought onto dairy farms in Australia is hay, and this is usually fed in equivalent amounts to grain. There is considerable variation in the amount and type of diet supplementation of lactating dairy cows, with grain inputs varying from 0–2.5 tons DM/cow/year and forage inputs varying from 0–1.4 ton DM/cow/year.

The U.S. Dairy Industry

The U.S. dairy industry has also been undergoing great change over the past twenty years. While the number of dairy cows has decline by 25% during this period, milk production has continued to increase (Figure 2). The dramatic increase in milk production per cow has been attributed mostly to enhanced genetics and associated improvements in animal nutrition, disease control, reproductive management, and other less important factors [22]. This marked trend of increasing milk production with fewer cows is likely to continue [123]. In 2006, the 9.1 million dairy cows in the U.S. produced on average 9,048 kg milk annually per cow. Projections for 2016 are 8.5 million cows producing 10,496 kg milk annually per cow.

Over the past 35–40 years, the number of dairy farms in the U.S. has also decreased dramatically. During the period 1969 to 1992, the number of farms decreased by 70% [74]. Between 1991 and 2006, dairy farm numbers have fallen from about 181,270 in 1991 to 75,140 in 2006. It has been forecasted that most

FIGURE 3. Percentages of national milk production in the U.S. produced on different dairy farm sizes, 1998–2006.



Source: USDA, [123].

increases in milk production over the next decade will come from the largest dairy farms. Whereas less than ten years ago most milk was produced on dairy farms having fewer than 200 cows, today most milk is produced on farms with greater than 500 cows (Figure 3).

NUTRIENT MANAGEMENT PRACTICES AND IMPLICATIONS ON DAIRY FARMS

A major goal of agriculture is to transform energy, water and nutrients into valuable commodities. Nutrients can be imported onto a dairy farm mainly in the form of fertilizer, feed, animals, through the fixation of atmospheric N by legumes, and to a lesser extent in bedding, irrigation water, or by atmospheric deposition. Nutrients are generally exported in milk, animals, manure, grains, and forage. The major nutrient flows, transformations and stores that occur within a dairy farm include:

- the intake of nutrients in feed and use to produce milk, increased body mass and calves;
- excretion in manure (urine and dung);
- the collection and storage of manure;
- the managed and unmanaged deposition of manure to soils;
- the addition of fertilizer and other plant nutrient sources to soil; and
- nutrient uptake by crops and pasture and subsequent storage in feed.

In many areas of intensive livestock production the amount of N and P applied to cropland and pastures often exceed requirements [59, 115, 45]. Nitrogen applications to cropland and pastures (in the forms of fertilizer, manure, legume N, and other organic sources), in excess of agronomic requirements, exacerbates N losses. Ammonia forms particulates, which results in haze, and is redeposited to cause acidification and eutrophication of surface waters. Nitrate leaching can contaminate ground water and increase losses of N via denitrification. While losses of N through denitrification constitutes only a small percentage (2–5%) of applied N, N_2O contributes significantly to global warming and ozone depletion. Long-term fertilizer and manure applications have created P surpluses [15]. Excess P has been shown to accumulate in soils on dairy farms in Australia and the U.S. [42, 58, 134, 75]. Increasing soil test P levels increases the concentration of dissolved P in surface runoff while P leaching losses may also be important when surface soils become saturated with P [38, 83, 113].

Managing Nutrients in Feed

As the N and P content of milk and meat are fairly constant, feeding dietary N and P in excess of animal requirements increases N and P excretion in dung and urine. When fed at recommended levels, only 25–35% of the N (crude protein) consumed by dairy cows is converted into milk [23]. Feed N not transformed into milk is excreted about equally in urine and dung. While N in dung is fairly constant at about 8 g/kg of feed consumed, the remaining excess N in feed is excreted in urine [105]. When fed at higher than recommended levels, excess protein is almost exclusively excreted in urine, which in turn can be converted rapidly and lost as ammonia gas to the atmosphere, or as nitrate, which is susceptible to leaching.

Excess feeding of P to livestock results in greater P concentrations in manure. In the U.S., inorganic dietary P supplements have been relatively inexpensive and have been added to dairy rations in the belief that this will increase milk production and conception rates in dairy cows [108]. While recommended feed P concentrations for dairy cattle are between 0.34–0.38%, many dairy farmers have been feeding 0.45–0.50% P in the diet [92]. Not only does excess dietary P result in greater P concentration in manure, but as the organic P fraction of manure stays fairly constant at around 0.6 g/kg of feed consumed, it also increases the proportion of water soluble orthophosphate, which in turn increases the risk of P losses in surface runoff [30, 32, 103, 105]. Excessive dietary P also decreases the N:P ratio of manure relative to N:P requirements of most crops [103]. This means that when manure from cows fed excessive amounts of P is applied to soil in amounts to meet a crop N demand (according to U.S.

regulations, this strategy is permissible for fields having medium or low soil test P levels) soil test P would increase much more quickly, thereby increasing the risk of runoff P, compared to the application of manure derived from cows fed diets that provide adequate amounts of P.

The use of total mixed rations and inorganic P supplements is not common on Australian dairy farms, and little is known about nutrient intakes and nutrient use efficiencies in grazing-based systems. It is likely that P intake will vary significantly between farms and seasons, and that excess P in diets is common. For example, dairy cows grazing pastures with markedly different P contents-ranging from 0.15–0.50% P, had corresponding P concentrations in feces ranging from 0.37–1.27% [2].

Manure Collection, Storage and Land-Application

There are distinct differences in how manure is collected, stored, and land-applied between grazing-based and confinement-based dairy operations. As a result of the common practice of year-round grazing, dairy manure in Australia is usually collected only from concreted areas such as the dairy parlor, holding yards, and feed pads. About 80% of Australian dairy farms have some sort of effluent management system, but the management of collected manure in these ponds is generally poor [9]. Effluent ponds are often not regularly emptied, and storage capacity is often too small for the effluent loads. Consequently, effluent ponds often overflow into adjoining paddocks. Even when effluent is applied to pastures in a managed way, it is often applied to readily accessible areas adjacent to the ponds, and rarely is the fertilizer value of the effluent taken into account.

In confinement dairy operations, manure collection, storage, and land application practices depend on how dairy cattle are housed, and vary with farm size. In the U.S., tie-stall barns are most common on confinement dairy farms having 100–125 cows or less, and free-stall barns are common on larger dairy farms [124]. In tie-stall barns, cows are confined to a stall, and manure is collected in a gutter behind the cows. Moderate to large amounts of straw, wood shavings, or crop residue are used for bedding. The manure mixed with bedding is typically removed with a gutter cleaner twice daily, and field applied daily or stored for later field application. Cows may have access to a small exercise lot, or may be allowed access to a pasture to graze for part of the day. In free-stall barns, cows are under roof and are free to move between stalls. Sand or mattresses covered with a minimum of bedding are generally used in free-stalls. Slurry manure is scraped two or three times per day from the concrete alleys, and is typically stored in an earthen or cement-lined pit that is emptied two or more times per year.

Similar to grazing-based operations, manure on confinement dairy farms may be deposited directly in outside cattle holding areas, such as barnyards, exercise lots, and feedbunk areas [99]. A recent study of manure collection practices on confinement dairy farms in Wisconsin found that collection was lower on farms that had tie-stall barns (66% of total annual production) than on farms that had free-stall housing (89%); and lower on farms having small to medium herds than on farms having large herds (Table 2). In outside cattle holding areas where manure is typically uncollected, average annual deposition of manure N ranged from 116 to 846 kg N/ha, average annual manure P deposition ranged from 24 to 158 kg P/ha, and soil test P and K levels are 20 to 30 times greater than what would be considered optimum for crop production.

TABLE 2. Regional housing type and herd class differences in manure collection on dairy farms in the Southwest (SW), South-central (SC) and Northeast (NE) regions of Wisconsin.

Category	Subcategory	Mean (SD)
Region	SW (18)[1]	56 (22.9) b[2]
	SC (18)	72 (21.8) a
	NE (18)	68 (21.5) ab
Housing type	Freestall (13)	89 (16.5) a
	Stanchion (34)	66 (18.9) b
Herd class	<50 cows (20)	57 (12.6) c
	50–99 (24)	76 (18.2) b
	100–199 (6)	95 (5.1) a
	200+ (4)	100 (0) a

[1] Farm numbers in parentheses. [2] Within a sub-category, means followed by different letters are significantly ($P<0.05$) different.
Source: Powell [99].

Having access to sufficient cropland for manure spreading is a prerequisite for proper manure management for confinement dairy operations. The amount of cropland needed for manure nutrient recycling depends on manure nutrient content, soil type, and the nutrient demands of the subsequent crop. What dairy cows consume can have a very large impact on manure nutrient levels, especially for P, and therefore the land requirement for effective manure management. For example, on Wisconsin dairy farms, approximately 0.7 ha of cropland is needed to recycle the manure P excreted by a lactating cow fed a P adequate diet [101. 102, 103]. Feeding P excessively can almost double this land requirement. There is increasing evidence that many dairy farmers have adopted practices as part of their whole-farm nutrient management plan that feed closer to cattle dietary P requirements with the goal of decreasing manure nutrient loads and therefore land requirements for manure spreading.

Fertilizer Applications

Since the middle part of the twentieth century, fertilizer use expanded greatly in Australia, the U.S., Europe, and other parts of the industrialized world. Before this period, agricultural production depended on the recycling of nutrients from animal manure or biological-N fixation by legumes. The widespread use of fertilizers and inexpensive transport transformed agriculture tremendously. Crops could be grown in one location, livestock produced in another, and human populations could live in remote urban centers [66].

When expressed in constant dollars, fertilizer prices world-wide have declined by 20% to 50% since 1960. Across all of U.S. agriculture, anhydrous ammonia use increased about five-fold and phosphate use increased about eight-fold between 1960 and 1970, while slower rates of increase occurred in use of potassium (K) and urea. Between 1970 and 1990, the use of anhydrous ammonia and phosphate declined. The decline in use of anhydrous ammonia occurred because of a greater availability of urea, lower hazards with handling and applying urea, and concerns about use of anhydrous ammonia for illegal drug manufacture. The decline in phosphate application may have been a response to increased concern about surface water contamination [97].

The most common fertilizer management practice on Australian dairy farms generally includes the application of superphosphate and potash in a single application prior to autumn growth, and it is often applied at a single rate over the entire farm. In the past fifteen years, N fertilizer use on dairy pastures has increased significantly [33]. The average N, P and K fertilizer applications for an Australian dairy farm equate to 16, 14, and 15 kg/ha/year respectively [73]. However, these average figures are skewed by large farms in more marginal environments, where the total land area is not used for intensive grazing and forage production, and individual farms will often apply in excess of 100 kg P, 400 kg N, and 180 kg K/ha/year, respectively.

While no general information is available on fertilizer use by dairy farmers in the U.S., recent information from Wisconsin suggests that dairy farmers integrate the nutrients contained in fertilizers, manure, and legumes much more than previously thought, with most effectively matching N and P inputs with crop requirements [89, 97, 116]. Of the total N applied to crops, 40% was derived from fertilizer, 30% from manure, and 30% from previous legumes, while for P, 70% came from manure, and 30% from fertilizer.

The efficiency of nutrients applied as fertilizer on pastures and crops is often low. For instance, in dairy pasture systems in Australia, less than 30% of P applied as fertilizer may be utilized in the year following application, with the remainder largely being fixed by soil and accumulating in poorly available forms [17]. While applied fertilizer N is not generally fixed by soils, N losses can be significant. Leaching of fertilizer N applied in wet and cold soil conditions can lead to losses of 20–40% [33, 69]. Ammonia volatilization is another important N loss pathway, particularly in moist soils with high pH. Volatilization from surfaced applied urea can typically range between 5–15%, but is generally between 5–10% from di-ammonium phosphate and < 3% from ammonium sulphate and ammonium nitrate [79].

Nutrient Transfers in Harvested Crops and Pasture

Another key mode for transfer of nutrients within dairy farms is through harvesting, storage, and feeding of conserved grain, crops, and forage. A typical ryegrass or alfalfa field in spring will contain approximately 40 mg/kg N, 25 mg/kg K, and 3 mg/kg P and therefore a 3 ton/ha hay or silage harvest would remove 120 kg N, 75 kg K, and 9 kg P/ha from the harvested field. This is generally stored and fed to cows, with nutrients transferred almost entirely into milk, meat, or manure.

The storage of conserved fodder or grain is itself not likely to result in significant nutrient losses. Although pit and bunker silage stores often lose as much as 20% of the mass prior to feeding due to the consumption of carbohydrates by microbes, N losses are likely to be small and P losses negligible. Similarly, only small amounts of P and soluble N are lost through the generation of silage leachate from high moisture silage stacks, while P and N losses from stored hay and wrapped silage should be negligible.

Heterogeneous Soil Nutrient Levels

Knowing the types, amounts, and availability of soil nutrients is an essential part of devising fertilizer practices that produce high-quality forage, grain, and pasture, while reducing potential environmental risks. Areas of low soil nutrient availability may cause reduced crop and pasture production, while high soil nutrient levels may contribute to high nutrient losses. Soil nutrient levels within a farm can be highly variable, due to differences in fertilizer and manure applications, crop/pasture yields and nutrient removal, and inherent soil characteristics.

In confinement systems, most manure is collected, stored, and land-applied. In pasture systems most manure is directly deposited in paddocks by grazing animals. Manure nutrient deposition by dairy cows is primarily a function of nutrient intake in forage and supplements, where animals spend their time, and the density of animals in that space.

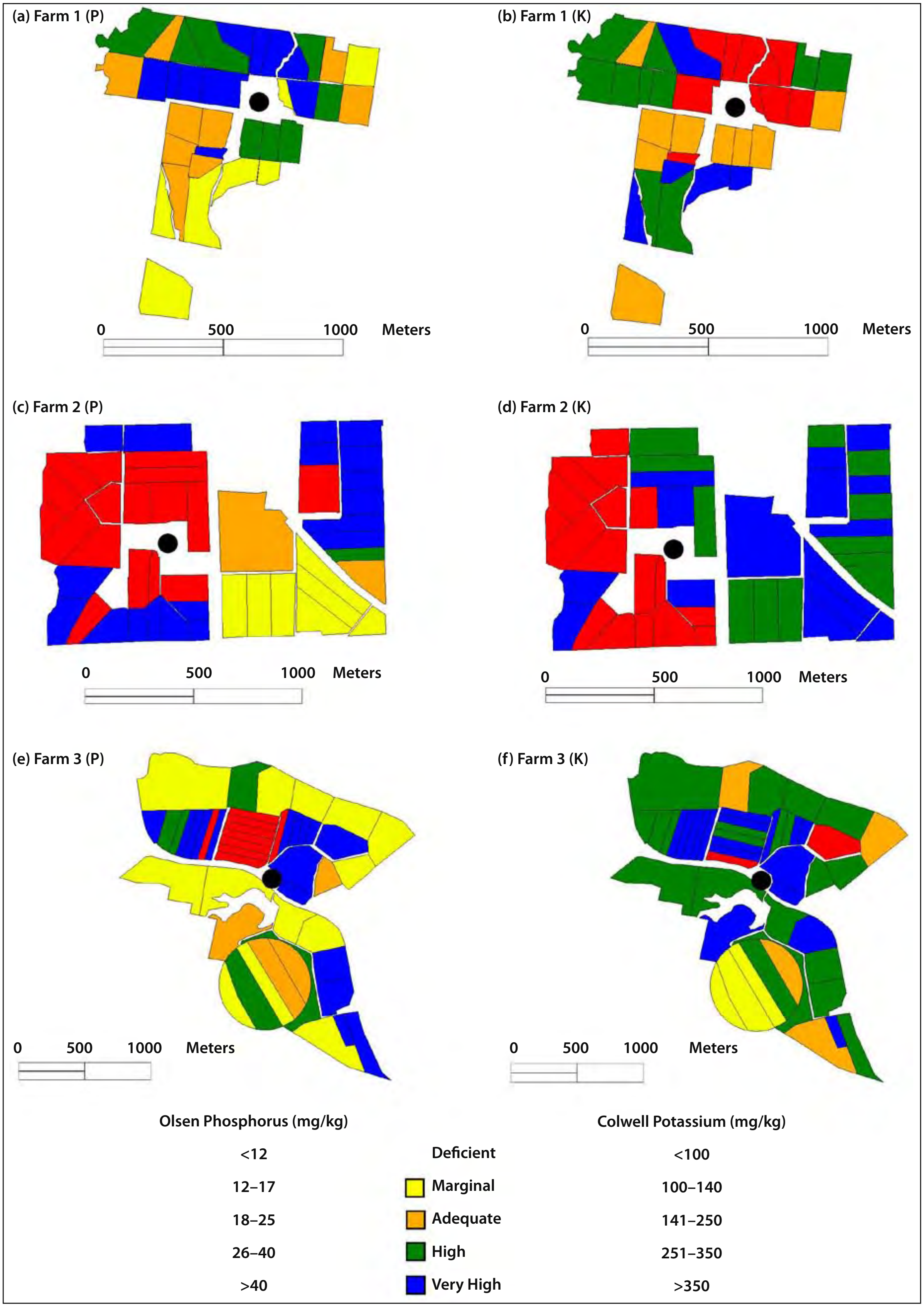
The nutrient loads in dairy cow dung and urine patches that occur in pastures are high. For example, the deposition of a single urine patch can apply the equivalent of between 500–1200 kg N and 200 kg K/ha [105]. A study investigating the chemical changes in soil directly under dung pads measured P and K application rates of 248 and 782 kg/ha, respectively, and found that manure applications doubled both soil P and K levels in the 0–5 cm layer after forty days [1].

Urine and dung deposition on pastures is not random. Within a dairy farm, areas which receive manure can be divided into four types: (1) areas where cows are confined, such as dairy shed, yards, and feed pads (manure is typically collected from these areas), (2) areas where cows choose (or are encouraged) to be in high densities, such as stock camps, shade and wind protection, gateways, watering points, and feed and mineral supply (manure is typically uncollected), (3) areas where cows are forced to be in high densities, such as laneways, feed pads, and sacrifice paddocks (most manure is typically uncollected), and (4) areas where cows are generally in low densities, such as when grazing pastures (manure is uncollected). Even within these areas, nutrient deposition will be variable. Cows will visit and forage in some paddocks more frequently than others due to proximity to the dairy, differences in annual yields, and the “locking up” of paddocks to conserve silage and hay. Cows will congregate and excrete more manure around gateways and water troughs, and shade areas. When paddocks are strip grazed and not back fenced (often to provide cows access to watering points), manure is deposited in greater amounts to the pre-grazed sections of the paddock.

The heterogeneous nature of soil nutrient levels within dairy farms can be demonstrated with detailed soil sampling and analysis at a field or sub-field basis. A study of nutrient distribution on twenty commercial dairy farms across Victoria, Australia found that P, sulfur (S) and potassium (K) soil test levels were highly variable, with substantially higher soil test levels associated with loafing paddocks in close proximity to the dairy, calving paddocks, summer sacrifice paddocks and where dairy effluent was regularly applied (examples are presented in Figure 4) [46]. Additional survey results from these farms suggest that cows spend a high proportion of time in these areas. Soil test levels were almost always lower in areas further away from the dairy, and where paddocks were regularly cut for hay and silage. Similar results from seven dairy farms in coastal New South Wales, Australia have been reported [67].

Aarons studied nutrient accumulation and distribution across thirty-three smaller areas surrounding the dairy, laneways, and stream on a commercial dairy farm, in Gippsland, Australia [1]. They found that soil

FIGURE 4. Soil phosphorus and potassium levels on three grazing-based dairy farms in south-eastern Australia.



The legend reflects agronomic soil test interpretation, • designates the location of the milking parlor.

test levels varied considerably, but were always well in excess of agronomic requirements. In the areas where cows congregate prior to entering the dairy yards, Olsen P levels in the surface 0–5 cm were in excess of 210 mg/kg. All of these studies concluded that the uneven distribution and accumulation of nutrients in areas within the farm is unlikely to be generating increased pasture production, as these areas often have soil test levels well above agronomic requirements, and therefore may be contributing disproportionately to nutrient loss.

Although manure applications to cropland is well recognized by farmers as a key component to overall nutrient management on confinement dairy farms, farmers may use only a relatively small fraction of their total cropland base for manure spreading. For example, a survey of manure spreading practices on 800 Wisconsin dairy farms determined that producers used on average only 23–44% of available cropland area (ha) for spreading manure [107]. Farmers' inability to use a greater proportion of their cropland area for manure spreading was associated with various factors, such as the presence or absence of manure storage facilities, labor availability and machinery capacity for manure spreading, the amount of manure actually collected, and therefore that needed to be spread on cropland, variations in the manure "spreading window", or days that manure can be spread given regional differences in weather and soil conditions, distances between where manure is produced and fields where manure is applied, and land tenure [90, 107].

In the U.S., as confinement dairy farms expand in response to rapidly changing market conditions, access to close-by or contiguous fields for manure application often becomes increasingly difficult. Manure spreading on distant, often rented land is time and energy consuming, and hence often not an economically viable option. Wisconsin dairy farmers apply manure more often to fields that are close to barns than to distant fields, although there appears to be regional differences in these practices [90, 97, 116, 117]. Similar to soil test distributions on grazing-based operations (Figure 4) soil test levels are much higher in fields close to barns where manure is applied more frequently than distant fields [19].

QUANTIFYING NUTRIENT FLOWS, TRANSFORMATIONS AND EFFICIENCIES ON DAIRY FARMS

Nutrient management planning for dairy farms has evolved over the last twenty-five years from a focus on soil nutrient requirements for crops, pasture, and livestock, to more integrated and comprehensive approaches which aim to quantify nutrient flows, identify opportunities for improvements in nutrient use efficiencies, and reduce nutrient losses to the environment. Nutrient management tools have been developed to integrate information across different scales, namely: (1) nutrient imports and exports at the whole-farm scale, (2) nutrient flows and efficiencies at the farm-system and component scale (i.e., feed, milk, manure, soil application, and plant uptake), and (3) soil nutrient status and nutrient loss, at the field/paddock scale.

Nutrient balances have been widely used to quantify nutrient flows, efficiencies and losses for dairy farms across these scales. In general they can be grouped into three categories: whole-farm balances, farm-system balances, and field-balances.

A whole-farm balance operates as a simple nutrient input-output model and integrates farm scale information into an environmental performance indicator. A surplus/deficit can be adjusted for changes in stored nutrients and is often used to estimate loss, especially for N. Farm-system balances attempt to determine nutrient inputs and outputs, changes in nutrient pools, and transformations of nutrients into farm products (i.e. feed nutrients transformed into milk and manure, fertilizer and manure nutrients incorporated into crop/pasture), and help to identify inefficiencies and processes of nutrient loss. A field-balance records nutrients that are applied to a particular field and leave the soil via harvested crop/pasture. Field balances are used for estimating the net loading of the soil with nutrients and can assist in refining nutrient distribution patterns within the landscape and associated risks of nutrient loss.

The choice of a nutrient balance approach depends on the intended purpose of the analysis, which should also define the scale, required accuracy, data required, and data collection strategy. Table 3 summarizes the associated benefits, limitations and uncertainties of each different nutrient balance approach [93]. Each nutrient balance has specific benefits, but become progressively more difficult to undertake due to increased costs and the uncertainties associated with the more detailed data requirements.

Whole-Farm Balances

Whole-farm nutrient balances have been used as indicators of potential nutrient losses, performance measures, to increase awareness about the importance of nutrient management, and as regulatory policy instruments to enforce specific nutrient management practices [94]. The approach has been widely adopted as a way of improving manure and fertilizer applications in the EU, and more recently has been strongly encouraged and supported in other dairy producing

TABLE 3. The benefits, limitations and uncertainties associated with different types of nutrient balances.

Type of balance	Benefits	Limitations	Uncertainties
Whole-farm	Relatively simple and uses readily available data Outputs are easy to communicate Possible to equate financially Repeatable	Fluxes not associated with managed transfers may not be included (deposition, N fixation, N leaching) Only applicable at a farm scale and may mask spatial heterogeneity Problem with carry over of nutrient pools between years	Minor if good book keeping by farmers
Farm- system	Inclusive accounting of all inputs and outputs Included internal cycling of nutrients through crop-animal-manure-soil transformations Allows for the separation of sources Increases understanding of nutrient cycling processes Sensitivity analysis can be done to identify major pools and fluxes Can separate spatial and temporal aspects of pools and fluxes over a range of scale	Data hungry and potentially more expensive More complicated to interpret	Data availability and quality is critical
Field	Allows assessment of accumulation or depletion from a soil pool Relates to crop / pasture production at a field scale Includes all inputs at a field scale	Does not distinguish between external and internal inputs and outputs Should not be extrapolated to the farm scale as may over-estimate fluxes Required estimates or predictions for N deposition, volatilization, fixation and leaching	Required soil test information, manure applications and concentrations Required yield, crop nutrient concentrations, soil profile information Difficult to get site specific data on N deposition, volatilization, fixation and leaching

Source: Modified from Obern [93].

countries such the U.S., Australia, and New Zealand [41, 42, 62, 118].

Whole-farm balances are the most common nutrient balance approach as they are generally easy to calculate from readily available data at a large scale and from sources that are likely to be fairly accurate [93]. These generally include "managed inputs" such as fertilizer and feed, as well as environmental inputs such as N fixation by legumes and atmospheric deposition (Figure 5). The importance of these inputs may vary substantially among farms, regions and countries, and will be influenced by factors such as farm size, stocking density (animals per unit crop land or pasture area), type of dairy operation (for example confinement versus grazing), management practices, level of imported feed and fertilizer, and soil and climatic conditions.

Whole-farm balances do not normally attempt to directly quantify environmental losses such as P runoff, N leaching, denitrification or N volatilization, as these are difficult to measure and are highly variable [96]. For N, soil N is generally assumed to be in a steady state, and "surplus" N is assumed to have been lost in gaseous forms or via leaching (Figure 5). Surplus P may accumulate in surface and sub-surface soil through soil fixation processes, though its fate is often difficult to accurately define [17].

A nutrient surplus or deficit can be calculated as the difference between nutrient inputs and outputs, usually standardized per ha of agricultural land and for a calendar year. For example:

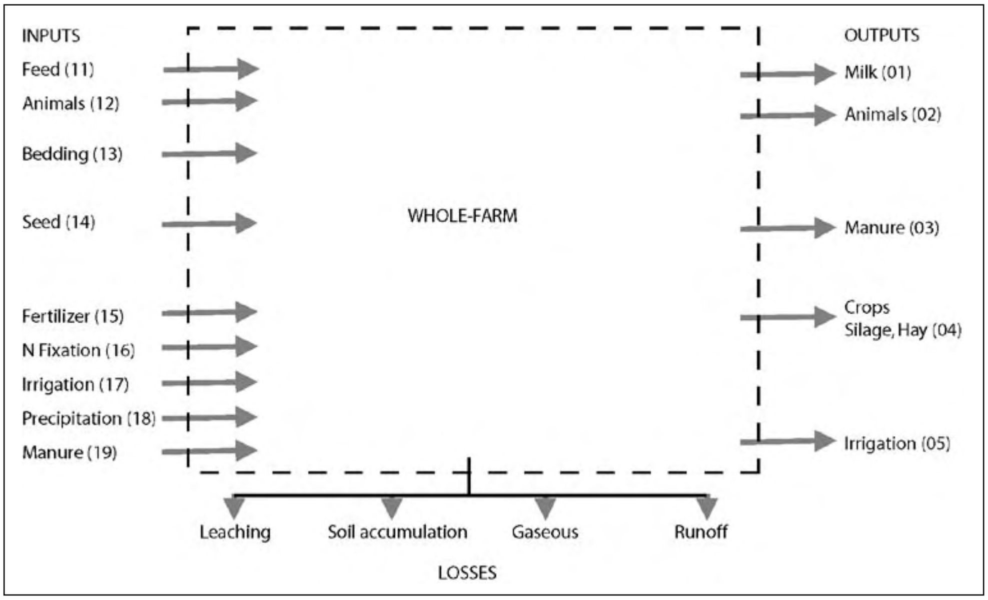
$$\text{Whole-farm nutrient surplus/deficit} = (I1 + I2 + I3 + I4 + I5 + I6 + I7 + I8 + I9) - (O1 + O2 + O3 + O4 + O5) \quad [1]$$

Whole farm "nutrient efficiencies" can be calculated as the relative amount of nutrient inputs divided by nutrients in exports. For example:

$$\text{Whole-farm nutrient efficiency} = (O1 + O2 + O3 + O4 + O5) / (I1 + I2 + I3 + I4 + I5 + I6 + I7 + I8 + I9) \quad [2]$$

Whole-farm nutrient balances have been used at the farm, catchment, regional, country and even global scales [12]. For example, at a country scale, historical and current national data sets in Belgium were used to determine N surpluses on an average dairy farm and concluded that N use efficiency had increased by about 8% between 1989 and 2001 [85]. At a statewide scale, input and production records were used to demonstrate that New York State had a decreasing P surplus from +50 million lbs in 1987 to +28 million lbs in 2002 [75]. Whole-farm nutrient balances have also been used to compare nutrient efficiencies or surpluses for dairy operations in different countries [68, 85, 130]. The Mineral Accounting System (MINAS) was used in The Netherlands to determine nutrient surpluses on dairy farms with different milk production levels in three dairy regions and on different soil types

FIGURE 5. Whole-farm nitrogen and phosphorus inputs and outputs for a dairy farm.



[52]. The Dutch yardstick was used to compare nutrient balances on different sized dairy farms in Wisconsin [36]. In the Cannonvale water supply catchment in New York State, the Cornell University Nutrient Management Planning System (cuNMPS) has been used to determine P and N surpluses at the farm scale, and then scale up these nutrient emissions to the catchment scale [24, 53].

P balances were developed for all agricultural enterprises in three degraded water quality catchments in southwest Western Australia to determine land use specific nutrient surpluses and efficiencies [86]. The New Zealand OVERSEER® model was used to assess current N and P surpluses, the potential N leaching losses, and impact of land use change, in three key catchments in New Zealand [104]. Dairy farm data from New York State (Table 4) was used to illustrate the increasing surplus of P as cow numbers per farm increased [60]. Similarly in Australia, P balances have been used to demonstrate the link between increasing stocking densities, fertilizer inputs, reliance on imported feed, and P accumulation on dairy farms (Table 5).

A whole-farm nutrient balance approach was used to determine N use efficiency in a farmlet study which compared no N and high N fertilized dairy pastures [68]. It was concluded that despite the 46% increase in milk yield from the farm, N use efficiency fell from 43% to 23%, and N surplus increased from 92 to 387 kg N/ha/year. At a similar scale, the effect of stocking rates and low rainfall conditions on the level of imported feed and associated K and P balances in a dairy farmlet study in Australia were studied [47]. Increased stocking rates and dry seasonal conditions resulted in a greater reliance on supplementary feed and an increased K and P surplus of three to four-fold (Table 6).

Farm-System Balances and Components

Biological systems are inherently inefficient in their use of nutrients and hence only a proportion of nutrients made available to animals and plants are transformed into products. For example, a dairy herd (milking cows, dry cows, and heifers) may transform only 15–20% of the N and P contained in feeds into milk production [126]. Also in these dairy systems, approximately 50–60% of the N and P applied to soil were found to be incorporated into pasture and crops.

Although nutrient use by plants are higher than animal nutrient use efficiencies, many dairy farmers continue to fertilize fields well in excess of crop nutrient demands. For example, in Wisconsin, in areas where manure has been land-spread, some farmers may not credit the manure nutrients applied, and apply high amounts of fertilizers [90, 97]. Overfeeding livestock

TABLE 4. Annual phosphorus balance for differing sized dairy farms, New York, U.S.

	Size of dairy, cows/farm			
	45	85	320	500
Item	kg P/year			
Inputs				
Purchased feed	907	1,542	7,619	12,880
Purchased fertilizer	1,088	816	1,814	9,070
Purchased animals	0	0	27	0
Outputs				
Milk	363	617	3,477	4,988
Meat	45	91	453	453
Crops sold	18	54	0	0
Remainder	1,569	1,596	5,530	16,509
% of Inputs	79	68	59	75

Source: Klausner [60].

TABLE 5. Annual phosphorus balance for dairy farms with different stocking densities in Victoria, Australia.

Item	Stocking rate 2 cows/ha	 3 cows/ha kg P/year	 4 cows/ha
Inputs			
Purchased feed	675	1,650	2,850
Purchased fertilizer	1,500	2,625	3,750
Purchased animals	0	0	0
Outputs			
Milk sales	750	1,200	1,575
Meat	43	65	97
Fodder	0	0	0
Remainder	1,382	3,010	4,928
% of Inputs	64	70	75

Source: Modified from Gourley [47].

and over-fertilizing fields result in lower nutrient use efficiencies and exacerbate the potential for nutrient surpluses and losses to the environment.

The principal advantage of a farm-system nutrient balance over a whole-farm balance is that in addition to imports and exports, it also provides information about nutrient flows, pools, and transformations within key production system components (Figure 6). Quantifying the fluxes and efficiencies of these nutrient flows and transformations within the farm-system is therefore an important part of identifying where improvements in nutrient use can be made.

Quantifying Nutrient Fluxes and Efficiencies. An important aspect of determining and interpreting nutrient fluxes and use efficiencies within key components of dairy operations is to establish standardized ways by which on-farm nutrient use measures can be compared. A number of recommended nutrient use efficiency definitions for confinement and grazing dairy operations are provided here.

Feed Nutrient Use Efficiency. Feed N and P use efficiencies are used to determine the relative amount of feed N and P transformed into milk. Establishing the relationship between feed nutrients and milk production is a logical first step in determining nutrient efficiencies within a farm-system. Feed N and P use efficiencies are calculated as:

$$\text{FNUE \%} = 100 \times (\text{Milk N production (g/cow/day)} / \text{Feed N intake (g/cow/day)}) \quad [3]$$

$$\text{FPUE \%} = 100 \times (\text{Milk P production (g/cow/day)} / \text{Feed P intake (g/cow/day)}) \quad [4]$$

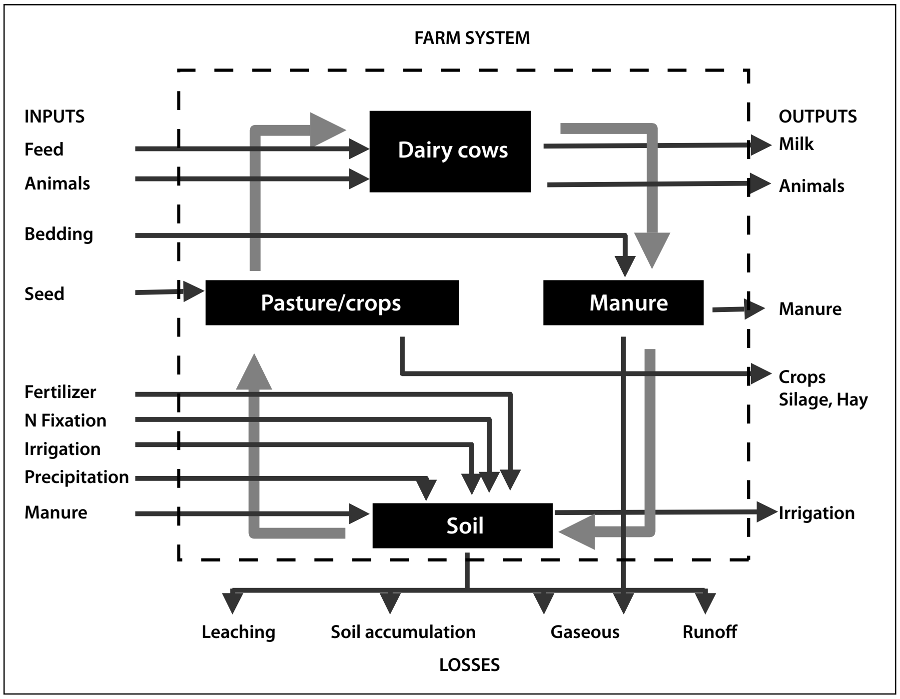
Manure N and P Excreted. As the N and P content of milk is fairly constant and mature lactating dairy cows utilize very little N and P for metabolism or growth, the amount of N and P excreted in manure is highly

TABLE 6. Potassium and phosphorus inputs in feed, outputs in milk and difference, for three stocking rates in a wet (1998–89) and dry (2000–01) season in Victoria, Australia.

	1998/99 2 cows/ha	 3 cows/ha	 4 cows/ha	2000/01 2 cows/ha	 3 cows/ha	 4 cows/ha
			Potassium (kg/ha)			
Feed	28	52	74	39	107	184
Milk	19	29	36	20	30	36
Difference	+9	+23	+38	+19	+77	+148
			Phosphorus (kg/ha)			
Feed	7	15	23	9	22	38
Milk	10	15	19	10	16	21
Difference	–3	0	+4	–1	+6	+17

Source: Gourley [42].

FIGURE 6. Farm-system balance describing whole-farm N and P inputs, outputs, and internal flow pathways for a dairy farm.



dependant on the dietary intake of N and P. Therefore N and P excreted in manure by a lactating dairy cow can be calculated by the following equations:

Manure N Excreted (g/day) = [Feed N intake (g/cow/d) – Milk N production (g/cow/d)] [5]

Manure P Excreted (g/day) = [Feed P intake (g/cow/d) – Milk P production (g/cow/d)] [6]

Manure Collection Efficiencies and Nutrient Loading Rates. Dairy cattle deposit manure in various farm locations, depending on the farms operational features and herd management practices. Farmers generally collect manure from some locations (e.g., barns, milking parlours) while manure in other locations may go uncollected (e.g., pastures, laneways, barnyards).

Accurately determining the amounts and efficiencies of manure collection and nutrient recycling on dairy farms can be difficult, especially for grazing operations. The amount of manure deposited in particular locations, and the subsequent efficiency of nutrient recycling on dairy farms, is generally determined by estimating the relative amount of time cattle spend in various farm locations and farmer collection practices. These calculations usually assume that deposition patterns are proportional to the amount of time dairy cattle spend in a particular location. Therefore nutrient deposition rates in a particular area and the collection and redistribution of nutrients to land is generally estimated from the following information:

- manure N and P excretions (g N and P/cow/day),
- where the manure nutrients were excreted (i.e. barns, barn yards, feed bunks, feed pads, milking parlor, holding paddocks, laneways, and grazed pastures),
- the size of each particular area,
- the number of cows that were present in each area,
- the proportion of each day cows spent in each area,
- what proportion of manure was collected from these areas,
- how manure was collected, and
- how collected manure was stored.

Manure Collection in Confinement-Based Dairy Operations. In confinement systems dairy producers may not collect all the manure excreted by their herd. This is particularly the case on dairy farms where cows spend significant time in pasture, barnyards, and other outside cattle holding areas. Knowing when, where, and how much manure is collected is a necessary first step in determining manure volumes, nutrient loads, and therefore how much land area is needed for manure applications. It is also important in determining the manure not collected and the potential accumulation areas and nutrient "hotspots" on dairy farms.

Manure collection efficiency (MCE) on confinement dairy farms can be calculated as follows [99]:

$$\text{MCE \%} = 100 \text{ x } (\text{Manure collected} / \text{Manure excreted}) \qquad [7]$$

On an annual basis, MCE can be estimated as the difference between manure excretion and the sum of farmer-estimated fractions of time cows spend in areas where manure goes uncollected, on a seasonal basis, determined as follows:

$$\text{AMCE \%} = (1 - [(Dp)(Yp) + (Ds)(Ys) + (Df)(Yf) + (Dw)(Yw)]) \times 100 \qquad [8]$$

Where the term AMCE represents the apparent manure collection efficiency for a cow type (lactating, dry, heifer); D represents time spent daily in outside areas where manure is not collected (fraction of days), as reported by farmers during spring (p), summer (s), fall (f), and winter (w); and Y represents a season's length (fraction of a year), as reported by farmers.

Manure Collection in Grazing-Based Dairy Operations. The major difference between nutrient recycling in grazing and confinement dairy farms is that in grazing-based dairy farms animals generally excrete the majority of manure directly on pastures, where as in confinement-based systems, manure needs to be collected and mechanically applied to croplands. Therefore, manure deposition and collection efficiency measures for grazing operations need to recognize the benefits and risks of non-collected manure directly deposited to pastures by animals, while also assessing the potential inefficiencies of manure deposited to non-pasture areas, such as laneways, sacrifice paddocks, and feed pads, where manure is not collected.

Manure excretion by cows directly onto pasture can be determined from the sum of farmer-estimated fractions of time cows spend on pastures, on a seasonal basis, determined as follows:

$$\text{MEP \%} = [(Pp)(Yp) + (Ps)(Ys) + (Pf)(Yf) + (Pw)(Yw)] \times 100 \qquad [9]$$

The term MEP represents the proportion of manure excreted directly onto pasture by lactating cows; P represents time spent daily (fraction of days) when cows are on pasture to graze, as reported by farmers during spring (p), summer (s), fall (f), and winter (w); and Y represents a season's length (fraction of a year), as reported by farmers. Further information provided by the farmers, regarding paddock rotations can be used to refine manure distribution patterns and estimated loading rates of N and P on a paddock basis.

Total manure excretion onto non-pasture areas of a grazing operation, such as feed pads, laneways, and the milking parlor, can be calculated as the difference between total manure excretion and manure excreted onto pasture as follows:

$$\text{MENP\%} = [(1 - (P_p)(Y_p)) + (1 - (P_s)(Y_s)) + (1 - (P_f)(Y_f)) + (1 - (P_w)(Y_w))] \times 100 \qquad [10]$$

The term MENP represents the proportion of manure excreted on non-pasture areas. Other variables are the same as described for equation 9.

Some of the manure deposited in non-pasture areas may be collected. For example, manure is generally flushed from milking parlors and collected in effluent ponds. Manure deposited on cement feed pads may also be scrapped or flushed into ponds. However manure deposited in laneways, stand-off areas and sacrifice areas, is usually not collected.

The proportion of manure excretion onto non-pasture areas of a grazing operation which is collected, can be determined from the sum of farmer-estimated fractions of time cows spent in areas where manure is collected on a seasonal basis, as follows:

$$\text{MENPC\%} = [(NPC_p)(Y_p) + (NPC_s)(Y_s) + (NPC_f)(Y_f) + (NPC_w)(Y_w)] \times 100 \qquad [11]$$

The term MENPC represents the proportion of manure excreted on areas other than pasture which is collected. NPC represents time spent daily (fractional days) when cows are on non-pasture surfaces where manure is collected, as reported by farmers during spring (p), summer (s), fall (f) and winter (w); and Y represents a season's length (fractional year), as reported by farmers.

Uncollected manure in non-pasture areas may pose the greatest environmental threat. Uncollected manure can lead to excessive nutrient loads in particular areas of the farm, which in turn increases greatly the risk of nutrient loss [1, 42, 99]. Knowing the amount of uncollected manure (kg), the nutrient concentration (g/kg), and the surface area (ha), nutrient loading rates (kg/ha) can be calculated for each non-pasture area.

Comparisons in the proportion of manure collected between confinement and grazing can be determined for both systems using equation 7. However, to compare manure collection efficiency among grazing operations (MCEG), manure directly excreted by animals on crop or pasture land should not be included. MCEG is therefore determined as:

$$\text{MCEG (\%)} = [\text{MENPC} / \text{MENP}] \times 100 \qquad [12]$$

The term MENPC represents the proportion of manure excreted onto non-pasture areas which is collected, and MENP represents the proportion of total manure excreted onto non-pasture areas.

The amounts of manure collected and uncollected on confinement (equation 7) and grazing (equation 12) dairy farms reflect manure nutrients at the time of excretion. They do not account for N and P losses after excretion. For collected manure, losses occur during manure collection, storage, and transportation to locations where manure is land-applied. Manure N losses generally range from 20–55% of excreted N for solid manure and 15–85% for liquid manure in various manure handling and storage systems [40]. Lost manure N mainly volatilizes as ammonia gas. Manure P losses range from 10–20% during manure collection, storage, and transportation [121]. Almost all of the lost manure P goes to the hydrosphere via soil surface runoff. Knowledge of manure N and P loss pathways and magnitude of losses are needed to estimate manure N and P collection and recycling efficiencies.

Nutrient Use Efficiency by Crops and Pasture. Dairy farmers apply fertilizer and manure, and supply other sources of organic nutrients (e.g., legume-fixed N) to cropland and pastures to enhance yields and feed quality (Figure 6). Soils also have inherent fertility which provides nutrients for plant uptake. There is tremendous variability in the type and amount of available soil nutrients. Because of the diversity of farmer's fertilizer practices and differences in soil fertility parameters, calculating nutrient use efficiencies for crops and pasture is much more difficult than feed nutrient use efficiencies. In general terms, crop and pasture nutrient use efficiencies (NUE) are calculated as follows:

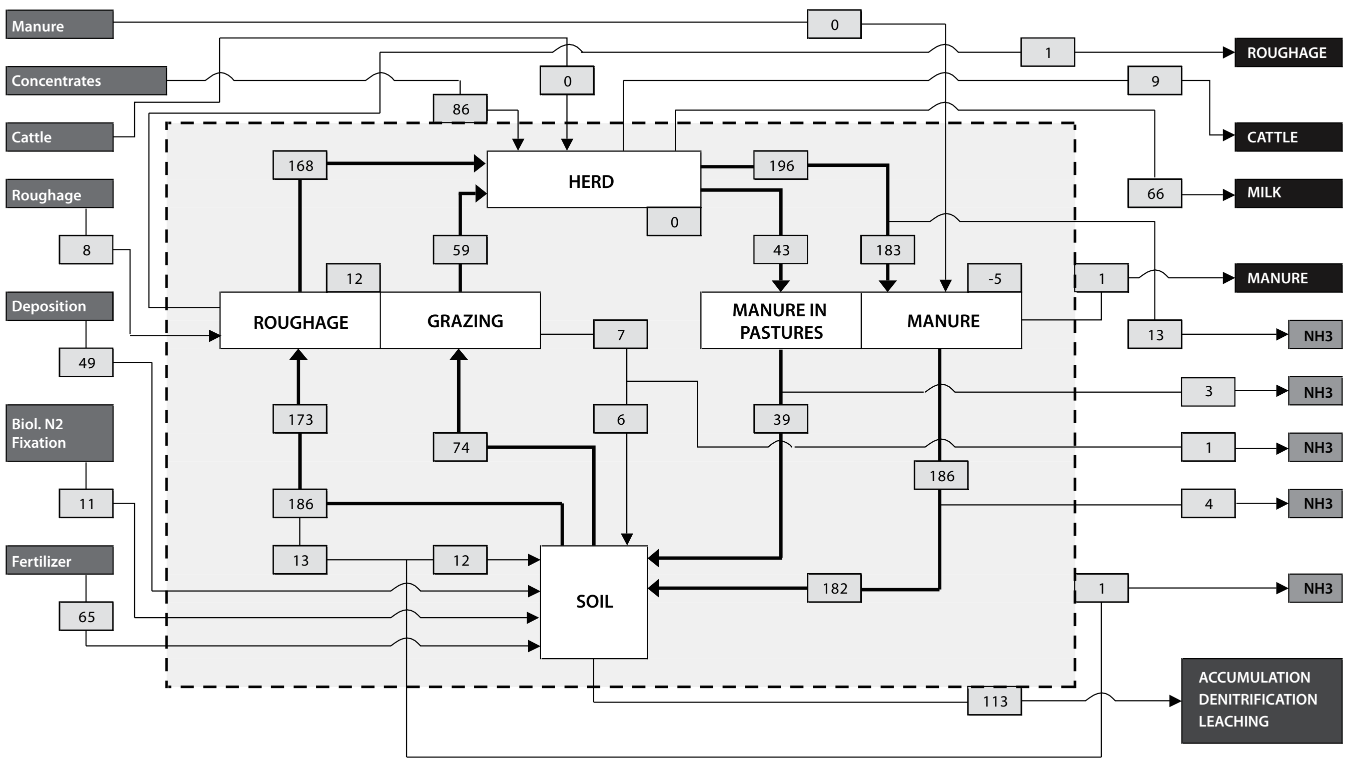
$$\text{NUE} = 100 \times \text{Crop nutrient uptake (kg/ha)} / [\text{Nutrient applied (kg/ha)} - \text{Nutrient uptake by “control crops” (kg/ha)}] \qquad [13]$$

The denominator in this equation accounts for the sum of all nutrients applied (e.g., fertilizer, manure) minus the amount of nutrients taken up by the crop in soil that received no nutrient additions (i.e. “control crops”). Such indirect estimates of nutrient uptake need to be interpreted with caution, due to uncertainties associated with nutrient availability in control plots. A more direct measure of NUE can be obtained by using expensive, isotopicly-labeled fertilizer and manure.

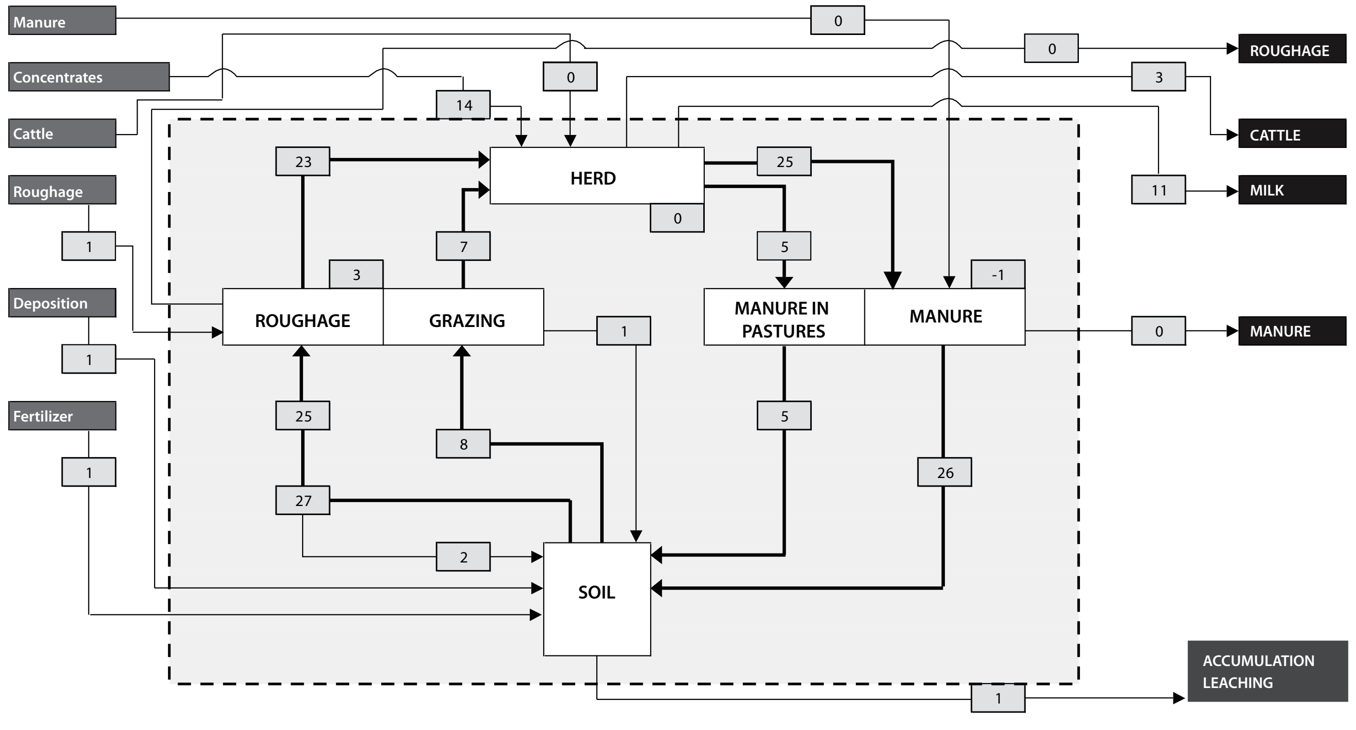
Examples of Nutrient Efficiency Measures on Dairy Farms. An example of annual N and P inputs, outputs, partitioning and flows among components within a dairy farm is provided from the De Marke experimental farm in The Netherlands [4, 5]. All N and P fluxes were measured or estimated during ten years (1993–2002) of operation (Figure 7). The nutrient balance data provides whole-farm assessments of N and P surplus, as well as the ability to determine efficiencies in nutrient utilization and subsequent inefficient processes on the farm. Based on the data provided from the De Marke project, average FNUE and FPUE were determined to be 21% and 25%, respectively [4, 5].

FNUE and FPUE on confinement dairy farms of the northeast region of the U.S. were found to range between 25–35% and 22–35 %, respectively and even under experimental conditions do not increase above 35% for N and 50% for P [55]. FNUE and FPUE was calculated for fifty-four confinement-based dairy farms in Wisconsin representing the range of herd sizes, feeding systems, housing types, and milking frequencies found in the state [84, 98, 129]. They found that average FNUE ranged from 18–33% (Table 7). Farms which used total mixed rations or balanced rations, and those that milked three times a day had the highest average N use efficiency. Average FPUE ranged from 18–35% (Table 7) and was significantly greater for those farms that balanced rations at least four times per year. The implications of a low feed use efficiency not only indicates wasted input costs but also has a

FIGURE 7. Average annual N and P inputs, outputs, and flows (kg/ha) through the major components for the De Marke experimental dairy farm in The Netherlands from 1993–2002.



Nitrogen Flows and Transformations



Phosphorus Flows and Transformations

Source: Modified from Aarts [4, 5].

TABLE 7. State-wide and regional values, and impact of herd size, feed management, and milking frequency on dietary crude protein (CP) and phosphorus (P) concentrations, dry matter intake (DMI), milk production, and feed N (FNUE) and feed P (FPUE) use efficiencies on Wisconsin dairy farms.

Parameter	Variables	CP	P	DM offer	Milk Prod.	FNUE	FPUE
		g/kg/DM		kg/cow/d[1]		%	%
State-wide values	Mean	172	4.1	22.7	29.6	25.4	29.0
	5th percentile	168	4.0	21.5	27.6	23.9	26.6
	95th percentile	175	4.3	23.9	31.6	27.0	31.3
Regional values	NE	172	4.2	23.8	31.8	27.1	29.5
	SC	173	4.0	22.3	29.6	25.1	29.0
	SW	172	4.3	22.1	27.3	23.8	28.4
Herd class	1–29	169	3.7b[1]	21.3	20.0c	18.2c	23.5b
(lactating cows/farm)[1]	30–49	168	4.2ab	23.6	27.4b	24.2b	26.6ab
	50–99	173	4.2ab	21.8	29.7b	26.6b	32.1ab
	100–199	175	4.0ab	25.3	33.1ab	24.3b	24.4b
	200+	176	4.5a	23.0	38.7a	32.6a	34.6a
Use of TMR	Yes	172	4.0	23.1	33.5a	27.0a	28.9
	No	172	4.2	22.5	26.1b	24.1b	29.0
Balance rations ≥4x y[1]	Yes	171	4.1	22.6	30.6a	26.5a	30.0a
	No	175	4.3	23.2	24.7b	21.0b	24.8b
Milk three times daily	Yes	176	4.5	23.0	40.2a	32.6a	34.6
	No	171	4.1	22.7	28.8b	24.9b	28.7
Use Posilac®	Yes	174	4.2	24.4	37.1a	29.0a	28.7
	No	171	4.1	22.4	27.7b	24.6b	29.1

[1] Within a variable category, means followed by different letters differ significantly (P<0.08).

Source: Adapted from Powell [98].

substantial impact on manure N and P concentration, which in turn can dramatically impact the area of land required to legally distribute collected manure [103].

Field Balances

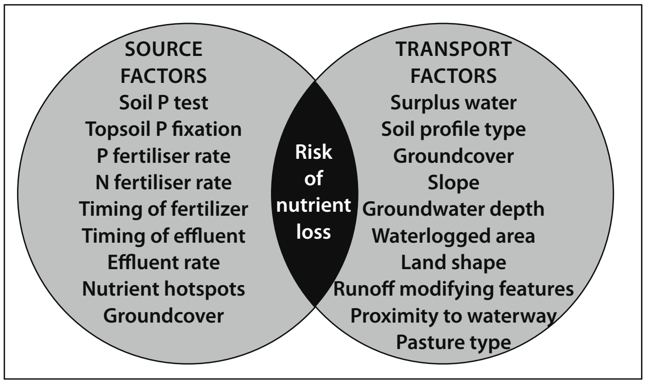
Defining Soil Fertility Targets. In Australia and the U.S., as in most other industrialized countries, soil analysis and interpretation is widely recognized as an important tool for improved soil-crop nutrient management decisions on farms. The use of soil-test information at the field/paddock level, can greatly assist in determining nutrient requirements for fertilizer and manure, and substantially improve soil nutrient use efficiency while reducing nutrient accumulation and losses. Subsequently, considerable effort has been directed towards developing and refining soil tests and soil-test calibrations, not only for providing fertilizer and manure advice, but also more recently, to assess the risk of nutrient loss.

Recently, renewed efforts in both Australia and New Zealand, have aimed to improve the accuracy of soil testing in pasture systems [34, 43]. For example, in Australia, data from more than 4,000 experimental trial years has recently been collated and re-analyzed to improve P, K and S soil-test pasture response calibration relationships [43]. Importantly, these revised soil-test calibrations are being used to redefine soil fertility targets and fertilizer applications by both fertilizer companies and government agencies.

Although dairy farmers and their advisors recognize that soil testing is a valuable tool in determining soil fertility levels on their farms, there is often a poor level of understanding of soil tests and their interpretation. An Australian study found that although 80% of the dairy farmers sampled pasture soils on their farms on a regular basis, only 50% were able to interpret soil test results effectively, and results were rarely used by farmers themselves to determine fertilizer requirements of individual fields, or to follow soil fertility trends over time [48].

Nutrient Loss Assessment. While the resources, time, and labor required for directly measuring nutrient losses in field-based studies can be high, the use of mechanistic and empirical models to predict nutrient losses are also complex and time-consuming to parametize and validate. Therefore a widely adopted approach has been to develop indices that assist in predicting the risk of nutrient loss from a field or part of the landscape. The risk of nutrient loss is the combination of the likelihood and magnitude of loss, as influenced by climatic conditions, landscape features, and land management. Nutrient loss indices are generally based on identifying key sources of nutrients and factors involved in transport and delivery to receiving waters. Where a high likelihood of nutrient transport and delivery coincides with a significant nutrient source, there is an increased risk of nutrient loss (Figure 8). The majority of work developing nutrient loss and environmental risk indices has been concerned with P.

FIGURE 8. A diagrammatic representation of factors influencing the source, transport, and risk of loss of nutrients.



Source: Gourley [43].

The development and adoption of nutrient loss indices is most advanced in the U.S. This is in part due to initiatives taken at a federal level that have prompted P loss indices to be incorporated into the nutrient management and water quality monitoring programs of most states [111]. The vast range of environmental, enterprise, and management scenarios present across the U.S. indicates the flexibility and robustness of the index approach.

The development and use of nutrient loss indices has been less in Australia than in the U.S. This is partly because there is less political imperative in Australia for farmers to meet environmental obligations. However, over the past five years, the Australian fertilizer industry and agricultural commodity groups, in association with government and university researchers, have been supporting and developing tools and voluntary approaches for environmental management, no doubt in the hope that this will limit restrictive legislation in the future. A significant outcome from this recent investment has been the Farm Nutrient Loss Index (FNLI), designed to aid grazing farmers, extension staff, and fertilizer advisors assess the spatial and temporal risks of P and N losses to surface waters, groundwater, and the atmosphere [77].

Since the potential for nutrient loss depends on a combination of characteristics specific to each paddock or land management unit, the appropriate management for each paddock can vary. For example, paddocks having similar soil fertility tests but different drainage characteristics, slope, pasture type, or management will have different risks of nutrient loss (Figure 9). Nutrient loss indices can therefore help land managers identify the risks of nutrient loss on different parts of their farms, explain why these risks occur, and explore nutrient management options, which can minimize nutrient losses.

A number of recent studies have attempted to validate P-indices using measured P losses at the field scale. For example, one study found that a P-index adequately predicted ($r^2 = 0.79 – 0.83$) the loss of P from manured and unmanured runoff plots [112]. Another study reported that P-indices had successfully reflected dissolved P in overland flow in Texas and in Arkansas [111]. A study also reported good to strong correlations ($r^2 = 0.58 – 0.74$) between runoff P and that predicted by the P-index [35]. These studies have also indicated potential improvements in these mod-

FIGURE 9. The combination of transport and source factors and associated risk of phosphorus loss for individual fields on a dairy farm as predicted by the Farm Nutrient Loss Index.

Drainage lines affect the amount of runoff.

Soil P affects the availablity of P (source factor).

Risk of P loss in runoff.

Source: Melland [77].

els. For example, when the weighting for erosion was increased from 1.5 to 7.5, the correlation increased to 0.85 [35]. At a larger scale, good correlations between P-index assessment and P concentrations in streams (r^2 = 0.51 – 0.70) and a lake (r^2 = 0.68) have been reported [13]. While these studies demonstrate strong relationships between P-index predictions and actual P losses in runoff, additional field evaluation and validation is still required [25, 71, 111].

NUTRIENT MANAGEMENT TOOLS FOR DAIRY FARMS

While the flow pathways of nutrients in and out of a dairy farm are generally consistent across dairy operations worldwide (i.e. feed, fertilizer, milk, and manure), within-farm nutrient cycling processes may be quite different between confinement-based and grazing-based dairy farms [105]. In confinement systems, a farmer has more control on feeding (amount, quality, and nutrient concentrations), which in turn influences milk production and the quantity and nutrient concentrations in manure. Additionally, within confinement operations there is potentially greater control over the capture and storage of excreted manure, and the application of manure to fields to meet crop nutrient demands. In contrast, a grazing system relies on the dairy cow to forage. Feed quality and nutrient content of pasture varies throughout the year, and the distribution of manure is uneven across the farm landscape and may accumulate in unproductive areas.

Most nutrient management planning tools developed in the U.S. are for confinement dairy farms and focus on manure management, and more recently, on feeding strategies to reduce nutrient concentrations in manure. In contrast, grazing-based dairy industries such as those in Australia and New Zealand, have developed nutrient management tools which have focused on fertilizer decisions and only recently have included issues such as nutrient balances and nutrient losses [42, 79]. Many of the recent and better integrated nutrient management planning tools have evolved from tools originally designed solely to optimize feed, manure applications, or fertilizer decisions.

The continuing interest in the development and use of nutrient management tools in most dairy regions of the industrialized world is mainly driven by their obligatory use to meet regulatory requirements, access financial support and co-payments from regional and federal governments, and to satisfy market access requirements. There is also interest from watershed management authorities and dairy companies in the use of nutrient management planning tools as a way of meeting "voluntary" environmental nutrient management standards [79]. Although less common, there is also growing interest by farm and fertilizer advisors in using nutrient management tools to help with nutrient management practices which support the business efficiency of dairy operations.

As a result of this growing interest, many different nutrient management tools for dairy farmers, advisors, researchers, and policy players have been developed. For example, the relative simplicity of whole-farm nutrient balances for dairy operations has led to the development of over forty-five different nutrient balancing tools in Europe [41]. On the other hand, more complex simulation models are more limited in number and are mostly used as research tools. Overall, currently available nutrient management tools vary greatly in terms of their objectives, degrees of complexity, data requirements, calculations, and ways of presenting outputs. Selecting the most appropriate tools presents a significant challenge for most farmers and advisors, and therefore they generally rely on tools that are locally developed and recommended by people they trust [76]. This, along with the need for site specific information, may help explain the diversity of different nutrient management tools available.

Examples of tools used to assist nutrient management decisions on dairy farms in Australia, the U.S., Europe, and New Zealand are provided in Table 8. These represent only a small proportion of the tools which are likely to be available. The characteristics of some of these discussed nutrient management tools used are summarized in Table 12.

The following descriptions of specific nutrient management tools serve to illustrate the range of nutrient management tools currently available, the scale at which they operate, the diversity of approaches taken, different inputs required and outputs generated, the key users, and widespread nature of their use.

Whole-Farm Nutrient Management Tools

Mineral Accounting System. The Mineral Accounting System (MINAS) was developed to reduce N and P surpluses and losses from livestock farms in The Netherlands and has played a key role in nutrient management advice and regulation of nutrient applications [82, 110]. The MINAS system has been used to determine N and P surplus on Dutch dairy farms since 2001 and farmers have been required to annually account for N and P imports, such as concentrates and forages, manure, fertilizer and animals, and N and P exports in milk and animals. Indirect inputs such as N deposition or N fixation were not included in the whole-farm balance [52].

The MINAS nutrient accounting approach continues to be an important policy instrument in the Dutch government's attempt to reduce nutrient losses and meet EU standards for reducing N leaching. Calculated N and P surpluses on dairy farms are compared to maximum allowable surpluses for particular operations and soil types, ranging from 60–250 kg/ha/year for N, and 8.8–15 kg/ha/year for P. Farmers are obliged to report their whole-farm nutrient inflows and outflows and

TABLE 8. Examples of nutrient management tools used in dairy production systems in Australia, the U.S., Europe, and New Zealand.

Country–State	Nutrient management tool	Reference
Australia	DairyMod	Johnson et al., 2005
	Dairy Nutrient Auditor	Gourley, 2004
	Farm Nutrient Loss Index (FNLI)	Gourley [43]
Denmark	Ethical account for livestock farms	Halberg [51]
France	Agro-ecological indicators	Bockstaller [14]
Sweden	Farm level nutrient balance (STANK)	Anon [10]
The Netherlands	Mineral accounting system (MINAS)	van den Brandt [128]
New Zealand	OVERSEER®	
UK	Environmental Management of Agriculture	Lewis [70]
U.S.		
California	Dairy facility nutrient assessment	California EPA [20]
Illinois/Missouri	Manure Management Planner	SNMP [119]
Maryland	Maryland nutrient balancer	Kohn [63]
Minnesota	Minnesota nutrient management plan	NMP [91]
New York	Cornell Cropware	Ketterings [57]
Pennsylvania	Integrated Farm System Model (IFSM)	Rotz [106]
Wisconsin	Modified Yardstick	Erb [36]
	N-CyCLE	Wattiaux [131]
	SNAP-PLUS	CALS [26]

have to pay a levy for each additional kg of N and P kg/ha above these defined standards [49].

Modified Yardstick. The Modified Dutch Yardstick is a whole-farm balance tool focusing on N, P, and K [36]. It is similar to a number of other nutrient balance tools currently available in a spreadsheet format [29, 56, 63]. The tool was originally developed in The Netherlands and was modified for use in the Upper Midwest of the U.S. in the mid 1990's. The Modified Yardstick is considered appropriate for farmer use, but has generally been used by advisors who are trained in data collection and can assist in interpretation. The Modified Yardstick was developed for dairy farms, but it is also applicable for cash grain operations and can be used on any farm where nutrient input-output data is available. Data inputs include livestock and animal products, purchased feed products, forages and minerals, sold crops, meat and milk, manure, N fixed by legumes, and atmospheric deposition. A basic N, P, and K surplus or deficit is then determined on a land area basis.

Farm-System and Component Nutrient Management Tools

Integrated Farm System Model. The Integrated Farm System Model (IFSM) is a whole-farm simulation model of dairy, beef, or crop production systems. Farm systems are simulated over many years to determine long-term performance, environmental impact, and economics of the farm. As such, the model is a long-term or strategic planning tool. All of the major processes of crop production (harvest, storage, feeding, animal production, manure handling, and crop establishment) are simulated, as well as the return of manure nutrients back to the land. By simulating various alternative technologies and/or management strategies on representative farms, the user can determine scenarios that provide the desired level of farm production, environmental impact, and profit.

IFSM has been used to model case study farms in The Netherlands (De Marke), New York, Pennsylvania, Washington, and New Zealand. Although farm level validation of these whole-farm models is very difficult, the IFSM model has satisfactorily reproduced the long-term feed production and use, and the N and P flows on commercial and research dairy farms [105].

An output table from the Integrated Farm System Model provides an example of farm scale N and P imports, exports and losses generated for a particular dairy farm over a twenty-five year simulation of climate and crop yields (Table 9).

IFSM and its predecessor Dairy Forage System Model (DAFOSYM) have primarily been used as research tools for evaluating alternative technologies and management strategies for dairy farms across the Northern U.S., Canada, and Northern Europe [100]. In addition to its primary purpose as a research tool, IFSM is also an effective teaching aid. Students, extension field staff, private consultants, and producers can use the model to learn more about the complexity of the many interactions that occur within a crop and livestock production system. However, the model's complexity tends to limit the use of IFSM by a wider audience. This level of complexity is necessary for the completeness and accuracy of the model in integrating the major processes and process interactions on a farm.

TABLE 9. An output table from IFSM providing nutrients imports, exports, and losses to the environment for a twenty-five-year analysis of a farm with 100 cows and eighty-five young stock on 220 acres of land.

	Unit	Mean	SD
Nitrogen imported to farm	lbs/ac	222.1	7.1
Nitrogen exported from farm	lbs/ac	66.9	
Nitrogen available on farm	lbs/ac	329.3	11.5
Nitrogen lost by volatilization	lbs/ac	64.3	2.4
Nitrogen lost by leaching	lbs/ac	30.2	8.4
Nitrogen lost by denitrification	lbs/ac	19.3	5.5
Average nitrogen concentration in leachate	ppm	12.3	5.1
Crop removal over that available on farm	%	51	4
Phosphorous imported to farm	lbs/ac	14.3	1.8
Phosphorous exported from farm	lbs/ac	11.5	0.7
Phosphorous available on farm	lbs/ac	21.2	0.3
Phosphorous loss through runoff	lbs/ac	1.1	0.0
Soil phosphorous build up	lbs/ac	1.7	2.2
Crop removal over that available on farm	%	87	11

Source: Powell [100].

DairyMod. DairyMod is a biophysical model of a dairy pasture system, which has been designed to simulate pasture and grazing management under Australian soil and climatic conditions [54]. The primary focus of earlier versions of DairyMod was to predict pasture growth and utilization, but the model has recently been expanded to investigate a broader range of issues and options. The principle components of DairyMod currently include a physiological pasture growth model that includes multiple species, animal intake based on bite dynamics, pasture heterogeneity and its influence on pasture growth and animal intake, water balance with evapotranspiration, infiltration and runoff, animal processes including lactation, pregnancy and growth, and fertilizer and irrigation strategies. The nutrient dynamics sub-models include predicting soil organic matter turnover, nutrient cycling and partitioning for N, P, K and S, and predictions of N losses from leaching, volatilization, and denitrification. Simulations are generally run for long time periods i.e. twenty years, using detailed climatic records.

A dairy farm can be divided into a maximum of 100 subdivisions or "paddocks," each of which can be parameterized independently to represent spatial variation in soil type, pasture type, fertilizer use and irrigation, or all combinations of these. The multiple paddock structure also allows for a realistic representation of rotational grazing.

The principal use of DairyMod is to investigate the interaction between management inputs and resource dynamics (water and nutrients), with a view to identifying efficient, sustainable management strategies. Users of the model require formal training and the setting up of scenarios for individual farms need detailed parameterization. Hence, DairyMod is principally used by Australian research scientists as a tool to compliment experimental programs and explore management options and implications. A simpler and more userfriendly version of DairyMod is currently being developed.

Nutrient Cycling in Crops, Livestock and the Environment. Nutrient Cycling in Crops, Livestock and the Environment (N-CyCLE) is a nutrient planning model which focuses on within-farm nutrient cycling processes and describes N and P flows and balances via feed, herd, manure, and fields [130]. The model aims to determine the best combination of crop rotations, dairy cow diets, and manure and fertilizer applications, with variable objectives that include (1) maximizing net income, (2) minimizing whole-farm P balance, or (3) minimizing the whole-farm N balance.

N-CyCLE evolved from a least-cost ration formulation model that predicted the best combination of crops to grow on a given land area, and feed to purchase to meet the herds' nutritional requirements [132]. Currently, N-CyCLE version 2.5, aims to optimize a whole-farm nutrient balance for N and P in as many as five groups of animals in the herd and five groups of fields [130]. It also provides an economic evaluation of management practices including those related to environmental management, such as the cost/benefit of reducing whole-farm N and P surpluses.

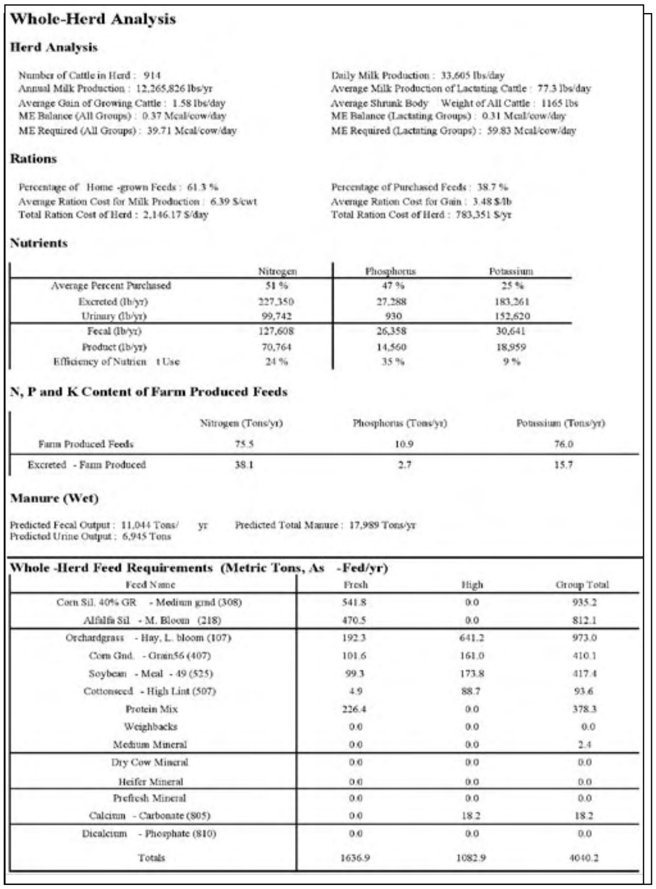
N-CyCLE was developed as a research and educational tool for teachers, researchers, and private consultants. The data input necessary to run the model is knowledge intensive and requires information on herd description, economic inputs, ration guidelines, feed composition, prices and losses, land units and crop rotation, and manure nutrient management and fertilizers.

Cornell University Nutrient Management Planning System. The Cornell Nutrient Management Planning System (cuNMPS) is an integrated decision support tool developed to merge nutrient use across livestock and crop components of a dairy farming system. It is composed of two key components: the Cornell Net Carbohydrate and Protein System (CNCPS Version 5.0), and Cornell Cropware [57]. Both components can also be used as stand-alone tools.

CNCPS is widely used across the U.S. and elsewhere to assist in formulating farm specific feeding programs for beef, dual purpose and dairy cattle based on consideration of the existing animals, feeds, management, and environmental conditions. The focus of the CNCPS is to reduce whole-farm N and P surplus through precision feeding of the whole-herd and utilization of home-grown feeds [39]. In addition to evaluating and improving rations for each group in the herd, the CNCPS is designed to predict whole-herd annual feed requirements (both home-grown and purchased), nutrient excretion (total and relative proportion from home-grown and purchased feeds), milk production levels, annual returns and feed costs, and whole-farm nutrient balances (Table 10).

The CNCPS model requires a large amount of input data, including individual animal and group parameters, feed amounts and analyses, and environmental and management conditions. Major regional variables that need to be determined are certain feed characteris-

TABLE 10. An output table from the Cornell Nutrient Management Planning Systems.



Whole-Herd Analysis

Herd Analysis

Number of Cattle in Herd : 914
Annual Milk Production : 12,265,826 lbs/yr
Average Gain of Growing Cattle : 1.58 lbs/day
ME Balance (All Groups) : 0.37 Mcal/cow/day
ME Required (All Groups) : 39.71 Mcal/cow/day

Daily Milk Production : 33,605 lbs/day
Average Milk Production of Lactating Cattle : 77.3 lbs/day
Average Shrunk Body Weight of All Cattle : 1165 lbs
ME Balance (Lactating Groups) : 0.31 Mcal/cow/day
ME Required (Lactating Groups) : 59.83 Mcal/cow/day

Rations

Percentage of Home -grown Feeds : 61.3 %
Average Ration Cost for Milk Production : 6.39 $/cwt
Total Ration Cost of Herd : 2,146.17 $/day

Percentage of Purchased Feeds : 38.7 %
Average Ration Cost for Gain : 3.48 $/lb
Total Ration Cost of Herd : 783,351 $/yr

Nutrients

	Nitrogen	Phosphorus	Potassium
Average Percent Purchased	51 %	47 %	25 %
Excreted (lb/yr)	227,350	27,288	183,261
Urinary (lb/yr)	99,742	930	152,620
Fecal (lb/yr)	127,608	26,358	30,641
Product (lb/yr)	70,764	14,560	18,959
Efficiency of Nutrien t Use	24 %	35 %	9 %

N, P and K Content of Farm Produced Feeds

	Nitrogen (Tons/yr)	Phosphorus (Tons/yr)	Potassium (Tons/yr)
Farm Produced Feeds	75.5	10.9	76.0
Excreted - Farm Produced	38.1	2.7	15.7

Manure (Wet)

Predicted Fecal Output : 11,044 Tons/ yr
Predicted Urine Output : 6,945 Tons
Predicted Total Manure : 17,989 Tons/yr

Whole -Herd Feed Requirements (Metric Tons, As -Fed/yr)

Feed Name	Fresh	High	Group Total
Corn Sil. 40% GR - Medium grnd (308)	541.8	0.0	935.2
Alfalfa Sil - M. Bloom (218)	470.5	0.0	812.1
Orchardgrass - Hay, L. bloom (107)	192.3	641.2	973.0
Corn Gnd. - Grain56 (407)	101.6	161.0	410.1
Soybean - Meal - 49 (525)	99.3	173.8	417.4
Cottonseed - High Lint (507)	4.9	88.7	93.6
Protein Mix	226.4	0.0	378.3
Weighbacks	0.0	0.0	0.0
Medium Mineral	0.0	0.0	2.4
Dry Cow Mineral	0.0	0.0	0.0
Heifer Mineral	0.0	0.0	0.0
Prefresh Mineral	0.0	0.0	0.0
Calcium - Carbonate (805)	0.0	18.2	18.2
Dicalcium - Phosphate (810)	0.0	0.0	0.0
Totals	1636.9	1082.9	4040.2

tics such as chemical analysis information. Feed libraries have been developed to accommodate regional differences, including data from North America, UK, Brazil, Mexico, South Africa, Korea, and Japan. All other variables are site specific and are entered by the user to characterize animal types, groups, farm management, and environmental conditions. CNCPS is currently being used in forty-two countries, primarily by nutritional consultants. The CNCPS model is also used as a teaching tool for students and consultants, as a research tool for identifying research priorities and designing and interpreting experiments.

Cornell Cropware is a software tool developed to help nutrient management planners and farmers make more efficient use of manure and fertilizers and also take account of a field's environmental risk. Cropware is mostly used in New York State to develop nutrient management plans at the whole-farm and individual field levels, in accordance with the government standards for nutrient management.

Cropware integrates (1) nutrient requirements for a full range of agronomic and vegetable crops; (2) nutrient credits from many sources, including manure, soil, and fertilizer; (3) equations for the conversion of soil test values from other laboratories; (4) environmental risk indices for N and P; and (5) on-farm logistics, such as manure production, storage, and inventories, into a detailed report for guiding on-farm implementation. While the concepts of balancing nutrients, applying nutrients based on crop needs, and assessment of risk of N and P losses, are transferable to other regions, equations within Cropware are based on New York State climate and soil characteristics and research outcomes. These include crop nutrient guidelines, yield potentials, fertilizer use efficiencies, soil N credits, organic N mineralization, ammonia volatilization rates for manure, the P index, and the N leaching index. Cropware is also used by educators, researchers, and students [57].

OVERSEER®. Nutrient balances have been used since the early 1990's to aid fertilizer decisions on New Zealand pastures [27]. Based on this early work, the OVERSEER® nutrient balance model has become the main decision support model for nutrient management on New Zealand dairy farms [135].

OVERSEER® determines whole-farm nutrient balances for N, P, K, and also S, Ca, Mg, Na, and H (acidity) and also operates as a farm-system balance, as it calculates nutrient use efficiencies, nutrient redistribution and losses within the farm. The model utilizes a wide range of farm-based information and management options including soil types, climatic conditions, animal types, stocking rates, supplementary feeding inputs and strategies, and fertilizer types and rates. Excreted N is estimated from N intake and the partitioning of N to milk, urine, and manure. N loss through leaching and volatilization is estimated from N excreted in urine and dung [68].

The use of OVERSEER® has increased markedly in recent years, as a wide range of groups, including researchers, dairy and fertilizer company advisory staff, and Regional Catchment Councils, have promoted the benefits from an environmental and production efficiency perspective (see [28] for a collection of New Zealand case studies). The two largest fertilizer companies in New Zealand provide the greatest contact with dairy farmers regarding nutrient management planning and have been strongly promoting whole-farm nutrient balances to dairy farmers, in association with soil testing and codes of practice for fertilizer use. Fontera Ltd, the major New Zealand dairy company which purchases around 95% of all milk produced, has committed all the dairy farms that supply milk to have undertaken a nutrient balance by 2007 [68].

Dairy Nutrient Auditor. The Dairy Nutrient Auditor is an Australian decision support tool designed to improve P, K, and S fertilizer recommendations on Australian dairy farms. The Dairy Nutrient Auditor uses inputs such as fertilizer and fodder purchases and milk sales to determine a whole-farm and paddock scale nutrient balance for P, K, and S. Within-farm nutrient transfers are estimated from individual paddock information, including pasture production, rotational grazing, supplementary feeding, fodder harvesting and feeding, stocking rates, and manure spreading practices. The Dairy Nutrient Auditor integrates within-farm nutrient transfers with soil test levels, soil type information, and soil fertility targets, to determine P, K, and S fertilizer requirements for each individual paddock or group of paddocks. While the primary focus of earlier versions of the Dairy Nutrient Auditor has been to improve P, K, and S fertilizer decisions, the model is currently being revised to include N and better refine and quantify nutrient flows, calculate efficiencies, and link to nutrient loss processes and pathways. The Dairy Nutrient Auditor is principally used by Australian research scientists and extension staff as a tool to compliment soil test interpretations and fertilizer recommendations.

Field Nutrient Management Tools

Manure Management Planner. The Manure Management Planner was developed by research and extension staff from Purdue University to assist in manure management planning for animal feeding operations, including poultry, pigs and dairy [78]. Information regarding fields, crops, manure production and storage, and application equipment is used to assist the user to allocate manure (where, when, and how much) on a monthly basis for the length of the plan (1–10 years). MMP also determines if the current operation has sufficient cropland area, seasonal land availability, manure storage capacity, and application equipment to manage the manure in accordance with legislative requirements. MMP is useful for identifying changes that may be needed for the current operation and if the operation expands. MMP can be tailored to different manure and fertilizer recommendations, and regulatory requirements, and is currently supported in twenty-one states in the U.S.

Spatial Nutrient Management Planner. The Spatial Nutrient Management Planner was developed by staff at the University of Missouri to facilitate the collection, analysis, and presentation of spatial information related to nutrient management planning [119]. SNMP provides a spatial context to manure management planning and is integrated with the MMP. The key strength of the SNMP is that it can automatically gather web-based geographic and climatic information such as property boundaries, soil types, topography, water-courses, and rainfall records for a particular farm and field. This information is then utilized in the development and presentation of an easy to follow nutrient management plan for farmers.

Michigan State University Nutrient Management. The Michigan State University Nutrient Management model assists crop and livestock producers with fertilizer and manure nutrient management and pesticide application record-keeping [80]. MSUNM contains the MSU "Fertilizer Recommendations" computer program which provides users with the convenience of generating their own MSU fertilizer recommendations by utilizing information from the university soil testing laboratories. MSUNM also allows the tracking of nutrient additions from fertilizer and manure applications, and can calculate manure application rates for fields.

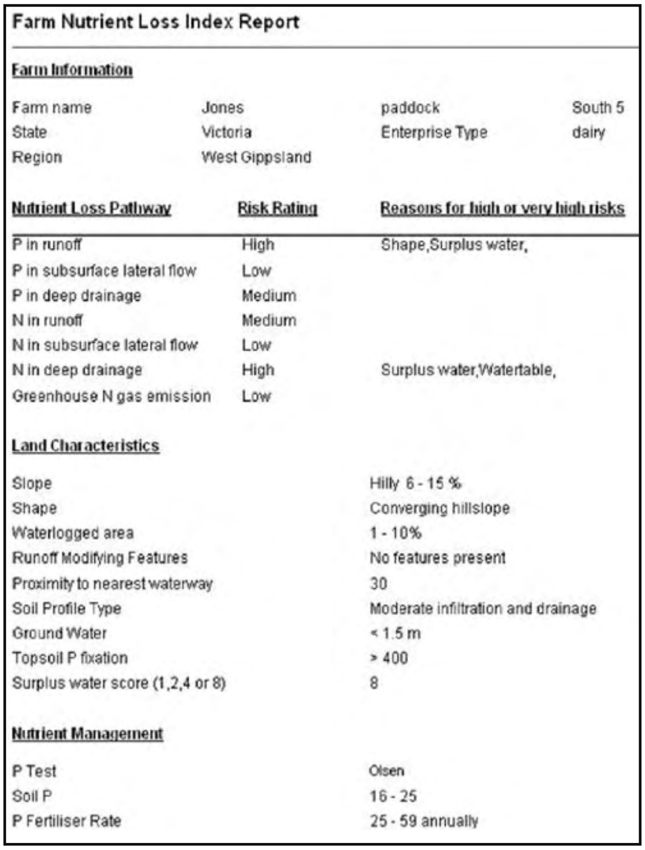
Nutrient Management Planning Model. The Nutrient Management Planning model (NMP) from the University of Minnesota is designed to assist in developing field specific nutrient management plans for crop and livestock farms [91]. The tool develops a nutrient plan for farms that receive state and federal support program funds, and also provides information for a manure-nutrient management plan that will meet the requirements of current Minnesota feedlot regulations. The NMP model includes a manure and crop nutrient calculator, which provides an analysis of the crop land area needed for utilizing the nutrients from manure applications (required for feedlot permit), and generates a manure-source report that gives the annual manure and nutrient production from the farm's manure storage systems. NMP also produces field-specific nutrient management plans which recommend annual manure and fertilizer applications, based on crop nutrient requirements, previous crop history, and past management practices.

SNAP-PLUS. SNAP-PLUS (Soil N and P) was developed by researchers at the University of Wisconsin as a nutrient management decision support tool for cropping systems [26]. SNAP-PLUS is designed to assist advisors and farmers to reduce N and P losses from farm fields, by estimating nutrient losses, and recommending improved management practices at both the field-scale and farm-scale.

Specific data requirements include farm location, land area, crops grown, fertilizers used and application methods, soil test data, livestock types, manure (source, percent collected, analysis and volumes), yield goals, soil tillage, and legume and manure credits. Output information includes soil loss estimates for each crop rotation and field, P loss estimates for each field by year and rotation, and whole-farm P and K balancing for each field by year and rotation; a field by field and whole-farm P-based nutrient management plan, and economic implications of current and proposed practices. SNAP-PLUS also includes suggestions of appropriate management practices from a range of options to decrease cost and/or environmental risks.

The intended users of SNAP-PLUS are farmers, federal and state natural resource managers, extension staff, consultants, teachers, and students. SNAP-PLUS uses data and research results specific to Wisconsin cropping systems and soil test recommendations for field and vegetable crops. The use of SNAP-PLUS enables crop and livestock producers in Wisconsin to meet the Natural Resources and Conservation Service (NRCS) Wisconsin 590 nutrient management standard, Confined Animal Feeding Operations (CAFO) regulations, soil conservation plans, manure management plans, and approved record-keeping.

TABLE 11. An example of a Farm Nutrient Loss Index paddock report, indicating the loss pathways, risk ratings and the factors contributing to high or very high risk outcomes.



Farm Nutrient Loss Index Report

Farm Information

Farm name	Jones	paddock	South 5
State	Victoria	Enterprise Type	dairy
Region	West Gippsland		

Nutrient Loss Pathway	Risk Rating	Reasons for high or very high risks
P in runoff	High	Shape,Surplus water,
P in subsurface lateral flow	Low	
P in deep drainage	Medium	
N in runoff	Medium	
N in subsurface lateral flow	Low	
N in deep drainage	High	Surplus water,Watertable,
Greenhouse N gas emission	Low	

Land Characteristics

Slope	Hilly 6 - 15 %
Shape	Converging hillslope
Waterlogged area	1 - 10%
Runoff Modifying Features	No features present
Proximity to nearest waterway	30
Soil Profile Type	Moderate infiltration and drainage
Ground Water	< 1.5 m
Topsoil P fixation	> 400
Surplus water score (1,2,4 or 8)	8

Nutrient Management

P Test	Olsen
Soil P	16 - 25
P Fertiliser Rate	25 - 59 annually

Farm Nutrient Loss Index. The Farm Nutrient Loss Index (FNLI) is an Australian decision support tool developed to aid grazing farmers and advisors assess the spatial and temporal risks of N and P losses to surface waters, groundwater, and the atmosphere [76]. The FNLI identifies the risk of N and P loss from individual paddocks via four nutrient loss pathways: runoff across the soil surface, drainage past the root zone, lateral flow within the root-zone of the soil profile, and emission of ammonia and nitrous oxide. For each paddock assessed, the FNLI identifies factors that pose a significant risk of nutrient loss and calculates a risk rating (low, medium, high or very high) for N and P, for each loss pathway. The FNLI is not designed to estimate actual loads or concentrations of nutrients lost from fields although the tool has been validated against measured nutrient loss data from seventeen field experiments across Australia.

High or very high risk ratings indicate that aspects of the grazing system may need to be modified to minimize potential nutrient loss. Where a high or very high risk rating is indicated, the main contributing factors are listed. These factors are either intrinsic features of the landscape, such as surplus water and soil type, or imposed by management, such as stocking rate. Alternative management practices can be tested to check strategies aimed at lowering the risk of nutrient loss. A summary of the risk results for each paddock can be saved and printed for future reference (Table 11).

In addition to its use by farmers and advisors, the FNLI is currently used as a training tool for fertilizer advisors and agronomists in the Australian Fertcare® accreditation program. A manual that provides information about the FNLI software, how the FNLI calculates risks, and the scientific principles of nutrient loss that underpin the index, is also available to the user.

TABLE 12. Characteristics of nutrient management tools for use on dairy farms in Europe, the U.S., Australia, and New Zealand.

	MINAS	**Yardstick**	**IFSYM**	**DairyMod**	**N-CyCLE**	**cuNMPS**	**OVERSEER**	**Nutrient Advisor**	**SNAP Plus**	**FNLI**
Environmental Outputs										
Phosphorus loss/balance	●	●	●	*	●	●	●	●	●	●
Nitrogen loss/balance	●	●	●	●	●	●	●		●	●
Other nutrient balances		●	●	*	●		●	●	●	
Manure timing/application					●				●	●
Economic inputs/outputs										
Income		●	●	●	●					
Manure/fertilizer costs			●	●			●	●		
Feed costs			●	●	●	●				
Production inputs/outputs										
Crop / pasture production	●		●	●	●			●		
Crop / pasture requirements				●		●	●			
Animal production	●		●	●	●	●		●		
Feed requirements			●	●	●	●		●	●	
Management decisions	●					●	●	●	●	●
Regulatory output[1]	●	●					●		●	
Record keeping output	●						●	●	●	●
Documentation available	●	●	●	*	*	●	●	*	*	*
Field validation	●	●	●			●	●	●	*	*
Targeted audience										
Farmer	●	●				●	●	●	●	●
Research	●	●	●	●	●	●	●	●		
Agricultural industry	●	●	●		●	●	●	●	●	●
Policy	●		●			●	●		●	
Teaching, Extension	●	●	●		●	●			●	●

[1] provides information that can be used to evaluate compliance to nutrient management regulations

*Documentation or development underway.

SUGGESTED IMPROVEMENTS TO NUTRIENT MANAGEMENT TOOLS

While much has been learned from existing nutrient management approaches and tools, there is also scope for improvement. Nutrient management tools that assess the basic inputs and outputs of nutrients on dairy farms, should also address the key internal issues of feed nutrient use, manure collection and storage, nutrient applications to soil, crop, and pasture uptake of applied nutrients, and soil nutrient accumulation and environmental losses. Such assessments and tool development are particularly needed for grazing-based operations, where this information is often lacking.

Nutrient management tool development would benefit from greater standardization of approaches and methods used for quantifying data inputs, and the assumptions and calculations used to determine outputs. The interpretation of generated outputs from nutrient management tools should be based on realistic farm performance measures and the associated uncertainties of model estimates. The farm financial and labor costs and returns for improving nutrient use efficiencies should be assessed and presented. It would also be useful to better demonstrate the linkage between improved on-farm nutrient management and environmental performance. A number of currently available nutrient management tools already address some of these issues. The following recommendations aim to assist in guiding the further development and refinement of nutrient management tools for dairy farms.

Greater Uniformity of Included Nutrient Sources

The accuracy and precision of any nutrient management tool depends on the approach adopted and the confidence in the available data. Despite the similar inputs, outputs, and transformations of nutrients for most dairy operations in the industrialized world, there are many modifications, assumptions, exclusions, and inclusions, associated with individual nutrient management tools. There may also be a considerable amount of uncertainty associated with the integration of farm information, which may lead to inappropriate estimates and recommendations.

While nutrient balances for dairy operations almost always include inputs such as feed and fertilizer, other nutrient sources such as bedding, N fixation, atmospheric deposition, and irrigation may not be included [93]. These exclusions are often justified when they are not relevant to the farm operations, for example where no irrigation is used or where there are no legumes grown, while others may rely on the assumption of steady state conditions, such is the case with animal numbers and mass. Sometimes, the exclusion of particular components may be justified on the basis that they only make minor contributions (for example, bedding, atmospheric deposition, and N fixation). However, if these assumptions are incorrect, it can lead to incorrect estimates of nutrient balances and efficiencies. Moreover, excluding components can result in nutrient management tools which are less standardized and applicable across a variety of dairy operations.

Similarly, there are numerous variations in the large number of nutrient loss indices which have been developed, particularly in the U.S. While transport, source, and watershed factors remain at the core of almost all P indexes, there are differences in which factors are included, and how they are used and modified [111]. For example, some indices adjust the importance of soil P test levels with additional soil information such as reactive aluminium, P absorption capacity, pH, or soil texture, while others do not. There are also a number of different approaches used to estimate erosion and surface runoff.

There are continued calls for greater consistency and standardized approaches to improve the confidence and applicability of nutrient management tools [41, 50, 93, 94, 122]. Greater uniformity in nutrient management tools will improve the quality, transparency, applicability, and interpretation of outputs and recommendations. This is particularly important from a policy perspective.

Uncertainties of Farm-Based Data

The data inputs and outputs for all nutrient management tools have a degree of uncertainty due to biases and errors. For example, the use of book values for nutrient concentrations in feed may not represent the actual nutrient concentrations, while analyzed subsamples of feed may have analytical biases and sampling errors. Studies involving nutrient accounting rarely present information about the uncertainty of the outputs presented.

The key data required for almost all nutrient management tools include mass/volume and nutrient concentration of the various nutrient sources and products. This is usually determined by a combination of farmer survey, to determine the type and amount of nutrient sources (i.e. feed purchased, fed or sold, milk production, fertilizer purchased, animal and crop/fodder sold), and "book" values of nutrient concentrations. This has the advantages of being efficient and using standardized nutrient concentration values, however there is rarely any validation of the data collected.

Developers of nutrient management tools should have realistic expectations about gathering data, keeping in mind their key user groups. For farmers and advisors this means that nutrient management tools should continue to focus on reliable and easy to collect data. The development of standardized on-farm record keeping systems that enable farmers and advisors to record relevant information at a time and place that suits their needs is likely to make data collection more efficient and accurate.

In the few studies where there has been validation of information provided by farmers, farmer derived information is generally shown to be reliable. In a study in Wisconsin involving 33 confinement dairy farms, feed and milk production data and information on manure land spreading practices provided by farmers was found to be consistent with established feed–milk–manure production relationships [98]. Another study to determine appropriate data collection methods for nutrient balances in Belgium found that on-farm surveys provided reliable assessments of mass of feed, and volumes of milk, but in contrast to other studies, concluded that information gathered about volumes of manure was not always reliable [81, 98]. These studies provide greater levels of confidence in survey type assessments of on-farm nutrient management, but more work is required to determine accurate and rapid survey instruments to assess nutrient management practices and efficiencies.

There are often good reasons to use book values or established algorithms to estimate nutrient concentrations, conversions, loading or loss rates. This is appropriate where data is hard to directly measure, or where the contribution is likely to be small relative to other components. However, the use of local reference data is recommended, as regional differences in these indirect inputs can be substantial [105]. Additionally, book values are appropriate where there is little variation in concentrations in components, or where there is a high level of confidence in the provided concentrations (such as in most commercial inorganic fertilizers). It is generally accepted that book values provide a reliable assessment of nutrient concentrations in livestock body mass and milk P [92, 81, 131]. Book values are also commonly used for nutrient concentrations in grains and forages, but these can vary substantially and can have a substantial impact on the resultant nutrient balance and efficiency outcomes [92].

Nitrogen fixation by legumes may be an important N input in both grazing-based and confinement-based dairy operations. In grazing systems, N inputs from legume N fixation can vary between 10 and 270 kg N/ha/year but is typically between 80 and 100 kg N/ha/year [69]. It has been suggested that N fixation by other forage legumes grown in monoculture may be much greater (100–200 kg N/ha/year) [105]. However, key limitations to N fixation include the amount and type of legumes present, soil moisture deficits, soil acidity, grazing pressure and N fertilizer applications and hence the contribution from N fixation may range between 0 and 300 kg N/ha/year, and may even be negative, depending on the harvest index of the crop, harvest frequency, existing soil N levels and climatic and management factors [69].

Determining the amount of N fixed by legumes is a difficult input to directly measure due to spatial and temporal variability and complex analytical techniques. Consequently, specific values or ranges of N fixation may be assumed or predicted using established algorithms and incorporated into nutrient management tools [64, 69, 81, 104, 105]. Wattiaux highlighted the importance of N fixation as a key input of N for confinement dairy operations in Wisconsin, but also demonstrated that by using different nutrient balance tools on the same eighteen Wisconsin dairy farms, inputs from N fixation were estimated at either 24 or 44% of the total N inputs [130].

It is important to reduce the potential uncertainties in data but it is also important to present uncertainties as part of the outputs from nutrient management tools. Oenema suggested four steps in dealing with the uncertainties of nutrient balances [94]:

1. Determine whether all relevant pools, inputs, and outputs have been identified.
2. Rank nutrient sources in terms of the estimated uncertainty.
3. Determine the actual degree of uncertainty for the various sources, i.e. mean and standard deviation.
4. Calculate the overall uncertainty for the nutrient balance. Analysis of uncertainties will also help identify where further research efforts are required.

Nutrient Efficiency Assessment in Grazing Operations

In confinement-based dairy operations, farmers generally have control of cow diets, which in turn influences the quantity and nutrient concentration of manure. Manure capture, storage, and land application is more controlled in confinement than in grazing dairy systems.

In grazing-based dairy operations, farmers generally have less control of diets, with feed quality and nutrient content varying throughout the year, and manure being predominately deposited directly by animals in the landscape. Moreover, nutrient management has received greater attention in confinement-based dairy operations from researchers, advisors, and farmers, and more is known about nutrient fluxes and efficiencies in these systems.

Despite the wide-spread belief that grazing-based systems are more environmentally benign than confinement-based systems, farm-scale nutrient surpluses, and uneven nutrient distribution and accumulation within parts of the farm may pose significant environmental challenges. There is clearly a need to improve our understanding of nutrient fluxes, distribution and use efficiencies within grazing-based dairy operations so that improved farm management strategies can be developed. Specifically, this includes determining the influence of farm characteristics, such as stocking rate and levels of imported feed and fertilizer inputs on whole-farm N and P surplus. Additionally, within-farm nutrient efficiencies for grazing-based dairy operations need to be better understood and quantified. For example, little is known about feed nutrient use efficiencies in grazing-based dairy operations. Similarly, manure distribution and nutrient loads in pasture and non-productive areas need to be better quantified and assessed in terms of the potential for nutrient loss.

Interpreting Nutrient Balances and Efficiencies

The interpretation of nutrient balance and within-farm nutrient use efficiencies needs to be done in the context of the farming operation and specific environmental conditions in which it operates. This benchmarking data is often scarce. For example, a high P surplus on a dairy farm with strong P fixing soils and low soil P status may result in a considerably lower risk of P loss than a much lower P surplus on a dairy farm with weak P fixing soils and a high soil P status. Moreover, a whole-farm N surplus of 160 kg/ha on a dairy farm may appear high, but knowledge that the minimum surplus achievable on similar soils is 140 kg N/ha and that 50% of farms in the region have a N surplus of >220 kg/ha changes the interpretation of this result considerably.

Rather than the unstated inference of achieving 100% nutrient efficiencies or “no net surplus,” the “potential” nutrient management standards for the whole farm, or nutrient management components within the farm (i.e. feed and pasture/crop nutrient and use efficiency, manure collection) are an important assessment criteria. These standards may be determined from politically set targets, modeled expectations, and detailed experimental work under controlled conditions. The goal or standard should more realistically be defined by “best practice” from a larger data set of farms with similar characteristics, which help to define the biologically achievable potential.

It is suggested that farm nutrient balance and efficiency information should be presented as the “actual” performance versus the “potential” performance, so that the information generated can be interpreted effectively and appropriately. With this information, farmers and advisors should be able to benchmark particular nutrient balance and efficiency information against a representative sample of similar farms. A better understanding of potential nutrient efficiencies would also better inform appropriate policy standards.

Linking Nutrient Use Efficiencies with Farm Profitability

It is generally recognized that information from nutrient management tools can assist farmers and advisors to target key management practices, improve nutrient efficiencies, and reduce nutrient surpluses. However, the use of nutrient management tools also requires necessary input data, which usually requires additional labor and operating costs. Changing on-farm nutrient management practices may also have associated labor requirements and costs and can impact farm profitability, either positively or negatively.

Farm-based data is generally available for many key nutrient sources, although not necessarily in the format or time scale required. Most farmers generally keep records of farm inputs and production outputs (i.e. fertilizer and feed purchases, milk and animals sold). Analysis of feed samples is common in confinement-based dairy operations, but rarely undertaken in grazing-based dairy operations due to perceived difficulties in collecting representative pasture samples and manipulating nutrient content. Manure sampling and analysis are also not generally undertaken in either grazing or confinement systems. Broad scale soil testing of individual fields/paddocks is also not widespread in grazing-based systems and is often seen as an unnecessary cost, despite the fact that the targeting of fertilizer and manure applications to meet agronomic nutrient requirements can significantly reduce fertilizer costs and increase crop/pasture productivity.

While solutions to nutrient excess and inefficiencies may present significant opportunities to reduce costs and increase profits, they may also increase costs and decrease profits. For example, while the reduction of mineral P supplements in mixed rations is likely to reduce feed costs, reducing dietary P by selecting low P protein supplements may increase costs [108]. Likewise, the requirement of hauling manure to more distant fields, particularly slurry, is likely to significantly increase both labor and fuel costs. In grazing-based systems, this may require the purchase of expensive pumps and irrigation equipment, far out-weighing any productivity gains that may come from recycling nutrients from collected manure.

Nutrient management tools that present information about the relative costs and benefits associated with improved nutrient management practices are more likely to assist farmers and advisors to make informed management decisions and seek support in addressing nutrient use inefficiencies.

Linking On-Farm Improvements to Reduced Nutrient Loss

Nutrient surpluses at a field level, and subsequent accumulation and losses to the broader environment, are often complex and highly variable throughout space and time. For example, excess P may be retained by soil and only slowly released through diffuse surface runoff processes, or alternatively lost in significant amounts during episodic erosion events. Phosphorus movement from a farm may also be retained in sediment in streams and water storages, and only be released in sufficient quantities to cause water quality impairment under specific environmental conditions.

There is ample evidence that nutrient management tools have improved farmer knowledge about nutrient flows and potential losses from their farms, and can significantly influence fertilizer and manure management decisions. However, there are few studies which have demonstrated improved water or air quality as a result of on-farm improvements in nutrient management practices [50, 111]. Work in The Netherlands using MINAS to guide nutrient applications on the De Marke research farm and sixteen dairy farms involved in the "cows and opportunities" project found reduced N and P contributions to groundwater [95]. At the catchment-scale, correlations have been found between farm-scale P surplus and catchment loads of P in northeastern U.S. and southwest Western Australia [21, 133]. More definitive evidence linking nutrient management improvements on farms with improved environmental outcomes would encourage greater adoption and use for nutrient management tools.

SUMMARY

The dairy industries in Australia and the U.S., as in other key dairying regions of the world, continue to undergo significant change. There are more cows kept on smaller land areas, and more feed is being purchased rather than home-grown. Greater cow numbers supported by the importation of relatively inexpensive feed and fertilizer has increased the risk of on-farm nutrient surplus, soil nutrient build-up, inefficient nutrient use, nutrient loss, and environmental pollution.

Improved nutrient management on Australian and U.S. dairy farms requires solutions to an array of system problems, such as excess feeding of nutrients, poor manure collection, storage and land-spreading techniques, broad-scale fertilizer applications, heterogeneous nutrient distribution through animal management, grazing and forage harvesting practices, and in some cases, farmers' unwillingness and/or inability to adopt improved practices.

To assist with integrating farm-based information with nutrient management decisions, many nutrient management tools have been developed and are available in Australia, the U.S., and elsewhere. These tools, either in part or as a whole, attempt to quantify nutrient imports and exports at the farm scale, nutrient flows and use efficiencies at the component scale, and soil fertility status and nutrient losses at the field and paddock scale. Future developments in nutrient management tools, for both grazing-based and confinement-based dairy operations, should strive for greater uniformity in methodologies, assess and present uncertainties around outputs, and improve the interpretation of generated information. There is also a need to develop more accurate and efficient ways of collecting on-farm data, and better link nutrient management recommendations with farm profitability and environmental outcomes.

REFERENCES

1. Aarons, S.R., A.R. Melland, C.J.P. Gourley. (2004). Nutrient distribution within a dairy farm. In "Supersoil 2004: 3rd Australian New Zealand Soils Conference 5–9 December 2004" (B. Singh, ed.). The Regional Institute Ltd, The University of Sydney, Australia. http://www.regional.org.au/au/asssi/supersoil2004/s13/oral/1619_Aaronss.htm.
2. Aarons, S.R., C.R. O'Connor, C.J.P. Gourley. (2001). Dung decomposition in temperate dairy pastures. Change in soil chemical properties. Australian Journal of Soil Research 42: 107–114.
3. Aarons, S.R. (2001). Cycling of organic phosphorus in grazed dairy pastures. Final report. Dairy Australia, Melbourne.
4. Aarts, H.F.M., B. Habekotte, H. Van Keulen. (2000a). Nitrogen management in the De Marke dairy farming system. Nutrient Cycling in Agroecosystems 56: 231–240.
5. Aarts, H.F.M., B. Habekotte, H. Van Keulen. (2000b). Phosphorus management in the De Marke dairy farming system. Nutrient Cycling in Agroecosystems 56: 219–229.
6. ABARE. (2006). Production systems, productivity, profit and technology. Australian Bureau of Agriculture and Resource Economics Paper 06.1 October 2006. www.abareconomics.com.
7. ABARE. (1985). Australian Bureau of Agriculture and Resource Economics 1985. www.abareconomics.com.
8. Anon. (2005). Final report of the International Conference on element balances as a tool for sustainable land management. Tirana Albania. March 13–19, 2005. http://www.pe.ipw.agrl.ethz.ch/research/Conf_pres/Final_Report_Tirana_DEF.pdf.
9. Anon. (2001). Sustaining our natural resources—dairying for tomorrow. Dairy Research and development Corporation Project report. National Land and Water resources Audit: 2001. http://www.greeningaustralia.org.au/nativevegetation/pages/pdf/Authors%20S/15_Dairy_RDC.pdf.

10. Anon. (2000). Stank Software and description. http://www.greppa.nu/net/SJV/Startsida.
11. ASEC. (2001). *Australia State of the Environment 2001*. Australian State of the Environment Committee. Collingwood, Victoria, Australia.
12. Bennett, E.M., S.R. Carpenter, N.F. Caraco. (2001). Human impact on erodable phosphorus and eutrophication: a global perspective. Bioscience 51: 227–234.
13. Birr, A.S. and D.J. Mulla. (2001). Evaluation of the phosphorus index in watersheds at the regional scale. Journal of Environmental Quality 30: 2018–2025.
14. Bockstaller, C, P. Girardin, H.M.G. van der Werf. (1997). The use of agro-ecological indicators for the evaluation of farming systems. European Journal Agronomy 7: 261–270.
15. Bundy, L.G. and S.J. Sturgul. (2001). A phosphorus balance for Wisconsin cropland. Journal of Soil and Water Conservation 56: 243–249.
16. Burkart, M.R., and D.E. James. (1999). Agricultural nitrogen contributions to hypoxia in the Gulf of Mexico. Journal of Environmental Quality 28:850–859.
17. Burkitt, L.L., C.J.P. Gourley, P.W.G. Sale. (2004). Phosphorus auditing can not account for all of the phosphorus applied to different pasture soils. Australian Journal of Soil Research 42: 89–98.
18. Burkitt, L.L., P. Moody, C.J.P. Gourley, M.C. Hannah. (2001). A simple phosphorus buffering index for Australian soils. Australian Journal of Soil Research 40: 1–18.
19. Cabot, P.E. and P. Nowak. (2005). Planned versus actual outcomes as a result of animal feeding operation decisions for managing phosphorus. Journal of Environmental Quality 34: 761–773.
20. California EPA. (2006). Central Valley Water Quality Control Board. http://www.waterboards.ca.gov/rwqcb5/available_documents/dairies/pdf.
21. Cassell, E.A., R.L. Kort, D.W. Meals, S.G. Aschmann, J.M. Dorioz, D.P. Anderson. (2001). Dynamic phosphorus mass balance modeling of large watersheds: long-term implications of management strategies. Water Science and Technology 43: 153–162.
22. CAST. (1999). *Animal Agriculture and Global Food Supply*. Task force report no. 135. Council for Agricultural Science and Technology. Ames Iowa, USA.
23. Castillo, A.R., E. Kebreab, D.E. Beever, and J. France. (2000). A review of efficiency of nitrogen utilisation in lactating dairy cows and its relationship with environmental pollution. Journal of Animal Feed Science 9:1–32.
24. Cerosaletti, P.E., D.G. Fox, L.E. Chase. (2004). Phosphorus reduction through precision feeding of dairy cattle. Journal Dairy Science 87: 2314–2323.
25. Coale, F.J., J.T. Sims, A.B. Leytem. (2002). Accelerated deployment of an agricultural nutrient management tool: The Maryland Phosphorus Site Index. Journal of Environmental Quality 31: 1471–79.
26. College of Agricultural and Life Sciences, University of Wisconsin-Madison (CALS). (2006). The Wisconsin buffer initiative final report to the Wisconsin Natural Resources Board. http://www.drs.wisc.edu/wbi.
27. Cornforth, I.S., A.G. Sinclair, J.S. Rowarth. (1993). The nutrition of grazed pastures in New Zealand. Plant and Soil 155: 227–230.
28. Currie, L.D., J.A. Hanly. (2006). "Implementing sustainable nutrient management strategies in agriculture." Report No. 19. 19th Annual Fertilizer and Lime Research Centre Workshop. Massey University, Palmerston North, New Zealand. http://flrc.massey.ac.nz.
29. de Vries, G.J.H., N. Middelkoop, G.A. Pak. (1998). The ecological sustainability of horticulture and agriculture. A comparison or organic and agromilieukeur. Centre for agriculture and the environment. Utrecht, The Netherlands.
30. Dou, Z., J.D. Ferguson, J. Fiorini, J.D. Toth, S.M. Alexander, L.E. Chase, C.M. Ryan, K.F. Knowlton, R.A. Kohm, A.B. Peterson, J.T. Sims, Z Wu. (2003). Phosphorus feeding levels and critical control points on dairy farms. Journal Dairy Science 86: 3787–3795.

31. Doyle, P., B. Fulkerson. (2001). The Australian dairy industry. Department of Natural Resources and Environment. Tatura, Victoria.
32. Ebeling, A.M., L.G. Bundy, T.W. Andraski, J.M. Powell. (2002). Dairy diet phosphorus effects on phosphorus losses in runoff from land-applied manure. Soil Science Society of America Proceedings 66: 284–291.
33. Eckard, R.J., D.F. Chapman, R.E. White, D. Chen. (2004). The environmental impact of nitrogen fertilizer use on dairy pastures. Australian Journal of Dairy Technology 59: 145–148.
34. Edmeades, D.C., A.K. Metherall, J.E. Waller, A.H.C. Roberts, J.D. Morton. (2006). Defining the relationships between pasture production and soil p and the development of a dynamic P model for New Zealand pastures; a review of recent developments. New Zealand Journal of Agricultural Research 49: 207–222.
35. Eghball, B., J.E. Gilley. (2001). Phosphorus risk assessment index evaluation using runoff measurements. Journal of Soil and Water Conservation 56: 202–211.
36. Erb, K., K. Fermanich. (2002). N, P and K balances across farm sizes: Do large dairies import more nutrients than small ones? In: Proceedings 2002 Wisconsin Fertilizer, Ag Lime and Pest Management Conference. January 2002. Madison, Wisconsin USA.
37. FAS. (2006). World dairy markets and trade. http://www.fas.usda.gov/psdonline/circulars/dairy.pdf.
38. Fortune, S., J. Lu, T.M. Addiscott, P.C. Brookes. (2005). Assessment of phosphorus leaching losses from arable land. Plant and Soil 269: 99–108.
39. Fox, D.G., L.O. Tedeschi, T.P. Tylutki, J.B. Russell, M.E. Van Amburgh, L.E. Chase, A.N. Pell, and T.R. Overton. (2004). The Cornell Net Carbohydrate and Protein System Model for evaluating herd nutrition and nutrient excretion. Animal Feed Science and Technology 112: 29–78.
40. Fulhage, C., J. Hoehne, D. Jone, R. Koelsch. (2001). Manure storage. In: MWPS-18 Manure management systems series. Mid-West Plan Service. Iowa University Press.
41. Goodlass, G., N. Halberg, G. Verschuur. (2003). Input output accounting systems in the European community—an appraisal of their usefulness in raising awareness of environmental problems. European Journal of Agronomy 20: 17–24.
42. Gourley, C.J.P., J.M. Powell, W.D. Dougherty, D. Weaver. (2007a). Improved nutrient management on commercial dairy farms in Australia. Australian Journal of Experimental Agriculture 47. (In press).
43. Gourley, C.J.P., A.R. Melland, R.A. Waller, I.M. Awty, A.P. Smith, K.I. Peverill, M.C. Hannah. (2007b). Better fertilizer decisions for grazed pastures in Australia. http://www.asris.csiro.au/themes/nutrient.html#Nutrient_BFD.
44. Gourley, C.J.P. (2005). Improved nutrient management on commercial dairy farms in Australia. Australian Journal of Dairy Technology 58: 148–54.
45. Gourley, C.J.P., I. Awty, P. Durling, J. Collins, A. Melland, S.R. Aarons. (2005). Heterogenous nutrient distribution across dairy grazing systems in South-eastern Australia. XX International Grassland Congress 2005: Offered papers. Dublin, Ireland. Wageningen Academic Publishers.
46. Gourley, C.J.P and A. Ridley. (2005). Controlling non-point pollution in Australian agricultural systems. Pedosphere 15 (6): 763–777.
47. Gourley, C.J.P. (2001). What is Australia doing in terms of dairy nutrient management and education? pp 70–81. In Nutrient management challenges in livestock and poultry operations: International and national perspective. 3rd Babcock Institute Workshop. August 21–24, 2001. Madison, Wisconsin, USA.
48. Gourley, C.J.P., J.A. Irvine, P.W.G. Sale. (1998). Fertilizer decision making by dairy farmers. Proc. Fertilizer Industry Federation of Australia conference. Perth, Western Australia.
49. Halberg, N., H. van der Werf, C. Basset-Mens, R. Dalgaard, I.J.M. de Boer. (2005a). Environmental assessment tools for evaluation and improvement of European livestock production systems. Livestock Production Science 96: 33–50.

50. Halberg, N., G. Verschuur, G. Goodlass. (2005b). Farm level environmental indicators; are they useful? An overview of green accounting systems for European farms. Agriculture, Ecosystems and Environment 105: 195–212.
51. Halberg, N. (1999). Indicators of resource use and environmental impacts for use in a decision support aid for Danish livestock farmers. Agriculture, Ecosystems and Environment 76: 17–30.
52. Hanegraaf, M.C., D. Jan den Boer. (2003). Perspectives and limitations of the Dutch mineral accounting system (MINAS). European Journal of Agronomy 20: 25–31.
53. Hudson J.L., R.E. Pitt, R.K. Koelsch, J.B. Houser, R.J. Wagenet. (1998). Improving dairy farm sustainability II: Environmental losses and nutrient flows. Journal Production Agriculture 11: 233–239.
54. Johnson, I.R., D.F. Chapman, A.J. Parsons, R.J. Eckard, W.J. Fulkerson. (2005). DairyMod: A biophysical simulation model of the Australian dairy system. http://afsa.asn.au/pdfs/johnsoniantheme2.pdf.
55. Jonker, J.S., R.A. Kohn, R.A., Erdman. (1998). Using milk urea nitrogen to predict nitrogen excretions and the utiliasation efficiency in lactating dairy cows. Journal Dairy Sceince 81: 2681–2692.
56. Ketterings, Q.M. (2007). Whole farm, nutrient balance spreadsheet. Nutrient Management Spear Program, Department of Crop and Soil Sciences. Cornell University. http://nmsp.css.cornell.edu/projects/massbalance.asp.
57. Ketterings, Q.M., G.L. Albrecht, C.N. Rasmussen, K.J. Czymmek. (2006). Cornell Cropware: A decision support tool for fertilizer and manure nutrient management planning. Journal of Natural Resources and Life Sciences Education 35: 140–151.
58. Ketterings, Q.M., J.E. Kahabka, W.S. Reid. (2005). Trends in phosphorus fertility of New York agricultural land. Journal of Soil and Water Conservation 60: 10–20.
59. Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. Journal of Environmental Quality 23: 139–147.
60. Klausner S. (1995). Nutrient Management Planning. In: K Steele (ed) Animal Waste and the Land-Water Interphase. pp 383–391. Lewis Publishers. New York.
61. Koch, B. (2002). Tool for integration—The Mangrove Information System (MAIS). http://www.biologie.uni-hamburg.de/bzf/oknu/proceedingsneotropecosys/p0813_krause.pdf.
62. Koelsch, R. (2005). Evaluating livestock system environmental performance with whole-farm nutrient balance. Journal Environmental Quality 34: 149–155.
63. Kohn, R.A. (2002). The Maryland nutrient balancer software. http:/www.agnr.umd.edu/nutrients/software.
64. Kristensen, E.S., H. Hogh-Jensen, I. S. Kristensen. (1995). A simple model for estimation of atmospherically derived nitrogen in grass clover systems. Biological Agriculture and Horticulture 12: 263–276.
65. Krogstad, T., O. Lovstad. (1991). Available soil phosphorus for planktonic blue-green algae in eutrophic lake water samples. Arch. Hydrobiology 122:117–128.
66. Lanyon, L.E., P.B. Thompson. (1996). Changing emphasis on farm production. In: Animal Agriculture and the Environment: Nutrients, Pathogens, and Community Relations. Pp. 15–23. Proceedings from the Animal Agriculture and the Environment North American Conference. Rochester, New York, USA. December 11–13. Ithaca, New York. Northeast Regional Agricultural Engineering Service.
67. Lawrie, R.A., E.J. Havilah, S.M. Eldridge, W.J. Dougherty. (2005). Phosphorus balance and distribution on dairy farms in coastal New South Wales. In "Supersoil 2004: 3rd Australian New Zealand Soils Conference December 5–9 , 2004" (B. Singh, ed.). The Regional Institute Ltd, The University of Sydney, Australia. http://www.regional.org.au/au/asssi/supersoil2004/s13/oral/1619_Lawrier.htm.
68. Ledgard, S.F., P.R. Journeaux, H. Furness, R.A. Petch, D.M. Wheeler. (2004). Use of nutrient accounting and management options for increasing nutrient use efficiency and reducing environmental emissions form New Zealand Dairy farms. OECD Expert Meeting on farm managemenet indicators and the environment. March 8–12, 2004. Palmerston North. http://www.oecd.org/agr/env/indicators.htm.

69. Ledgard, S.F. (2001). Nitrogen cycling in low input legume based agriculture, with emphasis on legume/grass pastures. Plant and Soil 228: 43–59.
70. Lewis, K.A., K.S. Bardon. (1998). A computer based informal environmental management system for agriculture. Environmental Models and Software 13: 123–137.
71. Leytem, A.B., J.T. Sims, F.J. Coale. (2003). On-farm evaluation of a phosphorus site index for Delaware. Journal of Soil and Water Conservation 58: 89–95.
72. Martin, P., P. Puangsumabe. (2004). Proceedings of the Gippsland Regional Agribusiness Outlook Conference. July 28, 2004. Australian Bureau of Agriculture and Resource Economics Paper 04.13. http://www.abareconomics.com/publications_html/conference/conference_04/conference_04.html.
73. Martin, T.G., K.M. Best, S. McIntyre, J.G. McIvor, N.D. MacLeod. (2000). Four grazing properties in S.E. Qld: Patterns of land use and ecological status. CSIRO Tropical Agriculture Technical Memorandum Vol. 5. Brisbane, Australia.
74. McBride, W. D. (1997). Change in U.S. livestock production, 1969–1992. Rural Economy Division. USDA-Economic Resources Services Agricultural Economics Report No. 754.
75. Mekken, J.C., S.N. Swink, Q.M. Ketterings. (2006). Statewide and county-based phosphorus balances for New York State. First Release. Department of Crop and Soil Sciences Extension Series E06-3. Cornell University, Ithaca New York. http://nmsp.css.cornell.edu.
76. Melland, A.R., S. Love, C.J.P. Gourley, R.J. Eckard. (2005). The development of trust in the development and delivery of a tool to reduce environmental nutrient losses from pasture systems. http://www.mssanz.org.au/modsim05/papers/melland.pdf.
77. Melland, A.R., C.J.P. Gourley, A.P. Smith, I. Tarbotton, K.I. Peverill. (2004). Developing a farm nutrient loss index for grazed pastures in Australia. In “Supersoil 2004: Program and Abstracts for the 3rd Australian New Zealand Soils Conference.” December 5–9, 2004. (B. Singh, ed.). The Regional Institute Ltd, The University of Sydney, Australia.
78. MMP. (2006). http://www.agry.purdue.edu/mmp.
79. Monaghan, R.M., M.J. Hedley, H.J. Di, R.W. McDowell, K.C. Cameron, S.F. Ledgard. (2007). Nutrient management in New Zealand pastures—Recent development and future issues. New Zealand Journal of Agricultural Research 50: 181–201.
80. MSUNM. (2006). http://www.msue.msu.edu/portal/default.cfm?pageset_id=25744&page_id=25794&msue_portal_id=25643.
81. Mulier, A., G. Hofman, E. Baecke, L. Carlier, D. De Brabander, G. De Groote, R. De Wilde, L. Fiems, G. Janssen, O. Van Cleemput, A. Van Herck, G. Van Huylenbroeck, I. Verbruggen. (2003). A methodology for the calculation of farm level N and P balances in Flemish agriculture. European Journal of Agronomy 20: 45–51.
82. Neeteson, J.J. (2000). Nitrogen and phosphorus management on Dutch dairy farms: legislation and strategies employed to meet the regulations. Biology and Fertility of Soils 30: 566–572.
83. Nelson, N.O., J.E. Parsons, R.L. Mikkelsen. (2005). Field-scale evaluation of phosphorus leaching in acid sandy soils receiving swine waste. Journal of Environmental Quality 34: 2024–2035.
84. Nennich, T.D., J.H. Harrison, L.M. van Weieringen, D. Meyer, A.J. Heinrichs, W.P. Weiss, N.R. St-Pierre, R.L.Kincaid, D.L. Davidson, E. Block. (2005). Prediction of manure and nutrient excretion from dairy cattle. Journal Dairy Science 88: 3721–3733.
85. Neven, F., I. Verbruggen, D. Reheul, G. Hofman. (2005). Farm gate nitrogen surpluses and nitrogen use efficiency of specialized dairy farms in Flanders: evolution and future goals. Agricultural Systems 82: 142–155.
86. Neville, S.D., D.M. Weaver, R.N. Summers, K. Lavell. (2005). Farm gate nutrient balances in south west Western Australia—an eco-efficiency indicator? Environment Institute of Australia and New Zealand, Environmental Sustainability in Practice Conference. March 29–April 1, 2005. Hotel Grand Chancellor, Christchurch, Australia.

87. Neville, S.D., D.M. Weaver. (2003). Avoiding the "fat" of the land: Case studies of agricultural nutrient balance. RipRap 25: 10–13.
88. NLWRA. (2000). Australian Water Resources Assessment 2000. National land and water resources audit. Canberra, Australia. http://audit.deh.gov.au/ANRA/water/docs/national/Water_Quality.html.
89. Nowak, P., R. Shepard, and F. Madison. (1998). Farmers and manure management: A critical analysis. In animal waste utilization: Effective use of manure as a soil rresource. (Hatfield, J.L. and Stewart, B.A. eds). Ann Arbor Press. Chelsea, Michigan, USA. 1–32.
90. Nowak, P., R. Shepard, and F. Madison. (1997). Farmers and manure management: A critical analysis. In animal waste utilization: Effective use of manure as a soil rresource. (Hatfield, J.L. and Stewart, B.A. eds). Ann Arbor Press. Chelsea, Michigan, USA. 1–32.
91. NMP. (2006). Minnesota Nutrient Management Plan. http://manure.coafes.umn.edu/assets/NutrientManagem entPlanner.pdf.
92. NRC. (2001). Nutrient requirements of dairy cattle. 7th Edition. National Academy Press. Washington, D.C, USA.
93. Oborn, I., A.C. Edwards, E. Witter, O. Oenema, K. Ivarsson, P.J.A. Withers, Nilsson, S.I. Richert, A. Stinzing. (2003). Element balances for sustainable nutrient management: A critical appraisal of their merits and limitations within an agronomic and environmental context. European Journal of Agronomy 20: 211–225.
94. Oenema, O., H. Kros, W. de Vries. (2003). Approaches and uncertainties in nutrient accounting: Implications for nutrient management and environmental policies. European Journal of Agronomy 20: 3–16.
95. Oenema, J., G.J. Koskamp, P.J. Galama. (2001). Guiding commercial pilot farms to bridge the gap between experimental and commercial dairy farms: the project "cows and opportunities." Netherlands Journal of Agricultural Science 49: 277–296.
96. Oenema, O., M. Heinen. (1999). Uncertainties in nutrient accounting due to biases and errors. In Nutrient disequilibria in agroecosystems: Concepts and case studies. (Smaling, E.M.A., Oenema, O. and Fresco, L.O. eds). CAB International. Wallingford. pp 75–97.
97. Powell, J.M., D.B. Jackson-Smith, D.F. McCrory, H. Saam., M. Mariola. (2007). Nutrient management behavior on Wisconsin dairy farms. Agronomy Journal 99: 211–219.
98. Powell, J.M, D.B. Jackson-Smith, D.F. McCrory, H. Saam., M. Mariola. (2006). Validation of feed and manure data collection on Wisconsin dairy farms. Journal Dairy Science 89: 2268–2278.
99. Powell, J.M., D. McCrory, D. Jackson-Smith, and H. Saam. (2005). Manure collection and distribution on Wisconsin dairy farms. Journal of Environmental Quality 34: 2036–2044.
100. Powell, J.M., Q. Ketterings, C. Rasmussen, L.N. Adams, G. Albrecht, K. Czymmek, A. Rotz, R.E. Muck, J. Norman, B. Stangel. (2004). Whole-farm nutrient management on dairy farms to improve profitability and reduce environment impacts. Cornell University Crop and Soil Sciences Research Series R04–1 and University of Wisconsin Extension Publication A3794.
101. Powell, J.M., D.B. Jackson-Smith, and L.D. Satter. (2003). Phosphorus feeding and manure nutrient recycling on Wisconsin dairy farms. Nutrient Cycling Agroecosystems 62: 277-286.
102. Powell, J.M., D. Jackson-Smith, L. Satter, L. Bundy. (2002). Whole-Farm phosphorus management on dairy farms. Proceedings Wisconsin Fertilizer Aglime and Pest Management Conference. January 17, 2002.
103. Powell, J.M., Z. Wu, L.D. Satter. (2001). Dairy diet effects on phosphorus cycles of cropland. Journal of Soil and Water Conservation 56: 22–26.
104. Power, I., S. Ledgard, R. Monaghan. (2002). Nutrient balance for three mixed farming catchments in New Zealand. Ministry and Forestry technical paper No. 2002/17. MAF information bureau, Wellington, New Zealand. http://search.maf.govt.nz/maf/publications.
105. Rotz, C.A., F. Taube, M.P. Russelle, J. Oenema, M.A. Sanderson, M. Wachendorf. (2005). Whole-farm perspectives of nutrient flows in grassland agriculture. Journal of Crop Science 23: 2139–2159.

106. Rotz, C.A., D.R. Mertens, D.R. Buckmaster, M.S. Allen, J.H. Harrison. (1999). A dairy herd model for use in whole-farm simulations. Journal of Dairy Science 82: 2826–2840.
107. Saam, H., J.M. Powell, D.B. Jackson-Smith, W.L. Bland, J. L. Posner. (2005). Use of animal density to estimate manure nutrient recycling ability of Wisconsin dairy farms. Agricultural Systems 84: 343–357.
108. Satter, L.D., T. Klopfenstein, G. Erickson, J.M. Powell. (2005). Phosphorus and dairy-beef nutrition. In: Phosphorus Agriculture and the Environment. ASA-CSSA-SSSA Monograph No. 46. (A.N. Sharply et al., ed.). Pp. 587–606. ASA-CSSA-SSSA, Madison, Wisconsin, USA.
109. Satter, L. (2001). Nutrient management in dairy production systems. In: Nutrient Management Challenge in Livestock and Poultry Operations: International and National Perspectives. Pp 38–53. Babcock Institute 3rd Technical Workshop. Madison Wisconsin, USA. August 21–24, 2001.
110. Schroder, J.J., H.F.M. Aarts, H.F.M. ten Berge, H. van Keulen, J.J. Neeteson. (2003). An evaluation of whole-farm nitrogen balances and related indicies for efficient nitrogen use. European Journal of Agronomy 20: 33–44.
111. Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A.J. Moore, G. Mullins. (2003). Development of phosphorus indices for nutrient management planning strategies in the United States. Journal of Soil and Water Conservation 58: 137–152.
112. Sharpley, A.N., R.W. McDowell, J.L. Weld and P.J.A.Kleinman. (2001). Assessing site vulnerability to phosphorus loss in an agricultural watershed. Journal Environmental Quality 30: 2026–2036.
113. Sharpley, A.N. (1995). Dependency of runoff phosphorus on extractable soil phosphorus. Journal Environmental Quality 24: 920–926.
114. Sharpley, A.N., P.J.A. Withers. (1994). The environmentally-sound management of agricultural phosphorus. Fertilizer Research 39: 133–146.
115. Sharpley, A.N., T.C. Daniel, D.R. Edwards. (1993). Phosphorus movement in the landscape. Journal of Production Agriculture 6: 453–500.
116. Shepard, R. (2005). Nutrient management planning: Is it the answer to better management? Journal of Soil and Water Conservation 60: 171–176.
117. Shepard, R. (2000). Nitrogen and phosphorus management on Wisconsin dairy farms: Lessons learned for agricultural water quality programs. Journal of Soil and Water Conservation 55: 63–68.
118. Sneath, G., H. Furness. (2006). Progress in developing and implementing nutrient management tools and systems for New Zealand agriculture. Implementing Sustainable Nutrient Management Strategies in Agriculture. Proceedings of the Fertilizer and Lime Workshop. (L.D. Currie and J.A. Hanly eds). 19th Annual Fertilizer and Lime Research Centre Workshop, Massey University, Palmerston North, New Zealand.
119. SNMP. (2006). Spatial nutrient management planner. http://www.cares.missouri.edu/snmp/index.html.
120. Steinfeld H.,P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. deHaan. (2006). Livestock’s Long Shadow: Environmental Issues and Options. FAO. Rome, Italy.
121. Sutton, A.L., D.D. Jones, B.C. Joern, D.M. Huber. (2006). Animal manure as a plant nutrient resource. Cooperative Extension Service ID-101. Purdue University. West Lafayette, Indiana, USA.
122. Sveinsson, T.H., N. Halberg, I.S. Kristensen. (1998). Problems associated with nutrient accounting and balances in mixed farming systems. Proceedings of the workshop on mixed farming systems in Europe. Dronten/wageningen. May 25–28, 1998.
123. USDA. (2007). USDA Agricultural Projections to 2016. Interagency Agricultural Projections Committee. Washington, DC, USA. http://www.usda.gov/oce/commodity/archive_projections/USDA%20Agricultural%20Projections%20to%202016.pdf.
124. USDA. (2004). Dairy 2002. Nutrient Management and the U.S. Dairy Industry in 2002. USDA Animal and Plant Health Inspection Service. Washington, DC, USA.
125. USEPA. (1996). Environmental indicators of water quality in the U.S. USEPA 841-R-96-002. USEPA, Office of Water (4503F). US Governemnt Printing Office. Washington, DC, USA.

126. Van Bruchem, J., S. Tamminga. (1997). Sustainability and the future of animal production: Options for environmental tuning of the systems in the Netherlands for nitrogen, phosphorus and potassium. Proceedings of the 47th Annual Meeting of the Canadian Society of Animal Science. Pp. 48–67. July 24–26, 1997. Montreal, Quebec, Canada.

127. Van de Meer, H.G. (2001). Reduction of nitrogen losses in dairy production systems: the Dutch experience. In: Nutrient Management Challenge in Livestock and Poultry Operations: International and National Perspectives. Pp 82–97. Babcock Institute 3rd Technical Workshop. Madison, Wisconsin, USA. August 21–24, 2001.

128. Van den Brandt, H.P., H.P. Smits. (1998). Mineral accounting: The way to combat eutrophication and to achieve the drinking water objective. Environmental Pollution 102: 705–709.

129. VandeHaar, M.J., N. St-Pierre. (2006). Major advances in nutrition: relevance to the sustainability of the dairy industry. Journal Dairy Science 89: 1280–1291.

130. Wattiaux M.A., D. Pellerin, S.A. Flis, E. Charbonneau. (2005). Economic and environmental analysis of whole-farm nitrogen and phosphorus balance and cycling in mixed livestock-crop farms. In AHAT-BSAS international conference.

131. Wattiaux, M.A. (2003). Optimization of whole-farm nutrient balance. An introduction. http:/dairynutrient.wisc.edu/N-CyCLE.

132. Wattiaux, M.A. (2001). A simple model to optimize feeding programs and crop rotation of dairy farms. In: Nutrient Management Challenge in Livestock and Poultry Operations: International and National Perspectives. Pp 54–69. Babcock Institute 3rd Technical Workshop. Madison Wisconsin, USA. August 21–24, 2001.

133. Weaver, D.M., S.D. Neville, R.N. Summers, M.F. Clarke. (2004). Reducing nutrient discharge from agriculture through the implementation of BMPs—how far can we go? Presented at the 7th International River Symposium. Brisbane Australia. August 31–September 3, 2004.

134. Weaver, D.M., A.E.D. Reed. (1998). Patterns of nutrient status and fertilizer practice on soils of the south coast of Western Australia. Agriculture, Ecosystems and Environment 67: 37–53.

135. Wheeler, D., S.F. Ledgard, R.M. Monaghan, R. McDowell, C. DeKlien. (2006). OVERSEER® development—what is it and what it does. In “Implementing Sustainable Nutrient Management Strategies in Agriculture.” Occassional Report No. 19. (L.D. Currie and J.A. Hanly eds.). 19th Annual Fertilizer and Lime Research Centre Workshop. Massey University, Palmerston North, New Zealand.

136. Wu, Z., L.D. Satter, A.J. Blohowiak, R.H. Stauffacher, J.H. Wison. (2001). Milk production, estimated phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. Journal Dairy Science 84: 1738–1748.