Guidance Document on Improving Nitrogen Management Using Nitrogen Budgets for Dairy Farms



International Nitrogen Management System

INMS Guidance Document Series

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About the International Nitrogen Management System (INMS)

INMS is a global science-support system for international nitrogen policy development established as a joint activity of the United Nations Environment Programme (UNEP) and the International Nitrogen Initiative (INI). It is supported with funding through the Global Environment Facility (GEF) and over 80 project partners through the 'Towards INMS' project (2017-2024). INMS provides a cross-cutting contribution to multiple programmes and intergovernmental conventions relevant for the nitrogen challenge. These include the Global Partnership on Nutrient Management (GPNM) and the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), the UN Convention on Biological Diversity (CBD) and the UNECE Convention on Long-Range Transboundary Air Pollution (Air Convention), through its Task Force on Reactive Nitrogen (TFRN). INMS receives major additional funding through the work of the GCRF (Global Challenge Research Fund) South Asian Nitrogen Hub, supported by UK Research & Innovation (UKRI).

Disclaimer

This document has been prepared as a scientifically independent contribution. The views and conclusions expressed are those of the authors, and do not necessarily reflect policies of the contributing organisations, GEF, UNEP or of the wider INMS membership.

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Cover photo

Dairy Farm in Ohio/USA by David Mark from Pixabay

INMS Guidance Document on Improving Nitrogen Management Using Nitrogen Budgets for Dairy Farms

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Foreword

Globally, the largest anthropogenic nitrogen flows are linked to agriculture. While this might change in the future, if green ammonia emerges as a major fuel as part of de-carbonization strategies, until now the nitrogen cycle has been dominated by agricultural activities. These include human endeavours to produce nitrogen fertilizers and to increase biological nitrogen fixation, thereby feeding humanity. Yet this is accompanied by massive losses of reactive nitrogen to the environment, causing a cascade of environmental impacts that threaten water, air and soil quality, affecting human health and contributing to biodiversity loss and climate change. Actively managing nitrogen on Planet Earth to maximize the benefits and reduce these pollution problems is a challenge that has only just begun.

The challenge has been recently recognized by the United Nations Environment Assembly, which has adopted two Resolutions on Sustainable Nitrogen Management (Resolutions 4/14 and 5/2 in 2019 and 2022). More ambitious still, the Colombo Declaration on Sustainable Nitrogen Management, adopted on UN Day, 24 October 2019, has set the ambition to halve nitrogen waste by 2030. In December 2022, it was followed up by the Kunming-Montreal Global Biodiversity Framework, under the UN Convention on Biological Diversity, with Target 7 embracing a global goal to at least halve pollution from excess nutrients (including both nitrogen and phosphorus) by 2030.

These agreements reflect major achievements in negotiation and raising awareness, but if they are to be more than pieces of paper, then guidance will be needed from the global scientific community on how to achieve these goals. This is exactly the work that the International Nitrogen Management System (INMS) is doing, supporting the work of the United Nations Environment Programme (UNEP), aided by financial support though the Global Environment Facility (GEF) and many other co-funders. The work of INMS includes bringing together scientists and others to assess the state of the threats and benefits, to prepare guidance on how to manage nitrogen better, and to raise awareness that can mobilize change, regionally and globally.

There are many dimensions to the global nitrogen challenge, so it has been essential for INMS to agree on priorities, especially on what guidance to provide. The present "INMS Guidance Document on Improving Nitrogen Management using Nitrogen Budgets for Dairy Farms" reflects one of these agreed priorities. With agriculture contributing the largest share of current anthropogenic nitrogen flows, most agricultural primary productivity is consumed by livestock, rather than by people directly (see the Our Nutrient World report). Of all the livestock types, it is cattle that contribute by far the largest share of nitrogen pollution. This reflects both the central importance of beef and dairy for global food production, as well as the modest nitrogen use efficiency typical of these systems. However, this guidance document should not be seen in isolation, but as part of the wider INMS Guidance Document Series, and as a first step in providing guidance in calculating and improving farm-level nitrogen budgets for different farm types.

This Guidance Document for dairy farms complements the INMS guidance documents on nitrogen use efficiency indicators, national nitrogen budgets and measures for mitigation of nitrogen pollution. In turn, these build on the UNECE Guidance Document on Ammonia Abatement and its Guidance Document on Integrated Sustainable Nitrogen Management. The present document clearly sets out the context, definitions and challenges in nitrogen budgeting for dairy farms. Importantly, it recognizes the wide diversity of systems and utilizes a typology of characteristic dairy farms with case studies to show how base-line efficiencies and nitrogen surpluses differ. This provides a starting point to consider the opportunities available to increase efficiency and reduce the amount of wasted reactive nitrogen resources. These are all managed systems. This means that, whatever the context, there are opportunities to do better, simultaneously enabling higher-efficiency food production, while reducing nitrogen waste and its contribution to nitrogen pollution.

We especially take this opportunity to thank Cameron Gourley and colleagues for their enthusiasm and dedication in taking up the challenge to prepare this Guidance Document. We gratefully acknowledge funding from GEF/UNEP for the 'Towards INMS' project and from UK Research and Innovation for support to the Global Challenges Research Fund (GCRF) South Asian Nitrogen Hub.

In launching this document, we invite National Focal Points of the UNEP Working Group on Nitrogen to share it with their colleagues around the world, especially as they develop their National Nitrogen Action Plans.

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Executive Summary

Dairy production is crucial for food security and the economic well-being of millions of farmers globally, while also requiring significant land, water and nutrient resources for the production of feed for milk producing animals. Reactive nitrogen (N) is a primary nutrient input to dairy production systems, improving feed quality, animal nutrition and milk production. However, the inefficient conversion of N inputs into feed, and from feed-N to milk, with the subsequent high content and often low plant recovery of N in excreta, results in various N transformations and loss pathways with a cascade of environmental impacts, including land, water and atmospheric pollution. Further, ruminant production is under increasing pressure from climate mitigation ambitions being the largest emitters of methane. Mitigation of methane and reactive N losses from dairy require an integrated approach.

The United Nations Sustainable Development Solutions Network has proposed that nitrogen use efficiency (NUE) should be an indicator of progress towards a goal to end hunger, achieve food security, improve nutrition, reduce pollution and promote sustainable agriculture. This is particularly relevant for dairy production due to the relatively high N inputs in many systems, their inherent N leakiness, and given an increasing trend for dairy intensification globally.

Nitrogen performance indicators are valuable for assessing N management practices and comparing N use outcomes and risk of N losses at the farm and paddock level. This includes optimizing N utilization across soil, forage, feeding and manure management practices, as well as animal husbandry, to enhance milk production.

Standardizing dairy farm NUE metrics and reporting frameworks will assist local and global dairy industry and policy makers to:

- Benchmark systems fairly on an international level,
- Identify systems and management practices that can improve NUE and reduce environmental losses, and
- Facilitate comparisons between different regions and countries and track NUE performance improvements over time.

This INMS guidance document on improving nitrogen management using nitrogen budgets for dairy systems incorporates guidance on N management and NUE indicators applicable to the broad range of dairy production systems, which operate globally. Guidance on NUE indicators for other systems can be found in Lassaletta and Sanz Cobeña (2026), while guidance on nitrogen budgets at a national scale is provided by Winiwarter *et al.* (2025).

Chapter 1: Background

1.1 General introduction

Dairy production is a vital part of food security and food choices and is practiced in nearly every country in the world. Dairy products are the fifth most important provider of energy and the third largest provider of protein and fat for human nutrition globally. Milk, cheese, butter and yogurt represent around 14% of global agricultural trade, with a total export value of about USD 80 billion in 2022 (OECD-FAO 2022).

Worldwide milk production is associated with the use of significant amounts of land, including extensive pastures and rangelands, as well as about 150 million hectares of arable land used for producing dairy feed materials (FAO 2020). Commonly, the production of these feed materials requires significant amounts of nutrients and water and can be associated with various environmental impacts.



Image 1. Small-scale farming in Kenya. Image courtesy of N Hutchings.

Reactive Nitrogen (N) is generally the largest nutrient input to dairy production systems, enhancing feed availability and quality, animal nutrition and milk production. However, the low conversion of N inputs into product, often with a large N surplus, as well as the various transformations and loss pathways of reactive N, can cause a cascade of environmental problems, such as land degradation, greenhouse gas emissions, water pollution and loss of biodiversity (Steinfeld *et al.* 2006).

To address these environmental concerns, improved and integrated N management practices are proposed, including improved N fertilization practices for crops and pastures, animal feeding and balanced diets, herd management and welfare, manure collection, storage and land application, and abatement measures to reduce ammonia (NH_3) and nitrous oxide (N_2O) emission and nitrate (NO_3^-) leaching and run-off.

Best N management practices have been summarized by Bittman *et al.* (2014) as:

- All N sources and N-cycling on the farm are understood and considered.
- Amounts of N used for plants and animals are not more than requirements.
- All N sources within the farm, especially manure, are collected, stored and reused effectively.
- All N sources are used in a timely manner, using best practice techniques.
- All possible N-loss pathways are considered and abatement measures implemented.

It is recognised that N performance indicators are particularly useful to evaluate N management practices and compare N use outcomes of an agricultural system and/or the risk of N losses at the farm and paddock scale.



Image 2. Grazing-based dairy system. Image courtesy of C Gourley.

Greater standardisation of within-farm dairy N use efficiency (NUE) metrics and reporting frameworks will enable the broader agricultural sector and policy makers to:

- equitably benchmark systems in an international context,
- identify systems and management decisions for improved farm productivity and reduced environmental losses, and
- enhance between-region/country comparisons and allow tracking of performance improvements over time.

This requires the development of internationally applied standards for quantification of NUE, including approaches for measurement and associated sensitivity, as well as application of NUE indicators within decision support systems.

1.2 Document purpose and intended users

Effective N management plays a crucial role in the productivity and environmental impact of dairy production systems worldwide. The goal of improving NUE is to maximize the benefits derived from both on-farm and commercial N resources, while minimizing N surplus and the emissions of reactive N to the surrounding environment.

This document offers guidance on N management and NUE indicators for the dairy sector and government advisors, promoting sustainable production that balances productivity with environmental and social concerns.



The information and indices provided aim to be applicable to the broad range of dairy production systems which operate globally. Dairy production systems with minimal N input and outputs, such as those dependent on common lands and nomadic grazing, are not addressed in this guidance document.

Image 3. Traditional Nepalese cow shelter and feed store. Image courtesy of K. Dahal.

1.3 How to use this document

To enhance N management and improve NUE, it is essential to integrate N fluxes more effectively at both the whole farm and within-farm scales. This involves optimizing N use throughout the continuum of soil, forage, feeding and manure management practices, as well as animal husbandry to maximize milk production.

Using appropriate indicators of NUE can help to monitor and evaluate the effectiveness of N management practices. Determining N input-output balances at the farm and component level is therefore required so that optimal N management practices can be established. Furthermore, enhanced N management seeks to identify and prevent pollution swapping across different N compounds and environmental compartments.

1.3.1 Goals of this document

- Describe dairy farm N fluxes and management strategies which can increase NUE and reduce reactive N emissions,
- Provide appropriate and practical NUE indicators for a range of global dairy farming systems,
- Provide case study examples of contrasting international dairy system typologies to demonstrate the use of whole-farm and component N budgets and NUE indicators.

Chapter 2: Global dairy production

2.1 Diversity of systems

Dairy farming is present in most countries and regions. There are approximately 133 million dairy farms globally (FAO 2020), with widely ranging production systems which include diverse per cow milk yields, animal breeds, feed types, grazing practices, housing and confinement infrastructure, and manure collection and reuse. Cow milk represents around 83% of global milk production.

Smallholder farms in developing countries, typically with only a few animals, use more traditional low-input systems that rely on indigenous breeds and low-cost feed resources, such as grazing of common pastures, crop residues and household waste. These dairy systems provide an essential source of food and livelihood, especially in rural areas.

In many developed countries, the dairy industry is generally dominated by commercial family farms which operate mixed dairy – cropping operations. Dairy animals are often housed or sheltered for up to 6 months. These farms may use sophisticated equipment, such as automated milking machines and computerized monitoring systems, to optimize herd health, milk quality and milk production.

Grazing-based dairy operations, most common in Oceania, generally involve medium or large dairy herds with no housing infrastructure. Intensively managed pastures with regular fertilization provide most of the fodder and feed intake. These systems often have seasonal variations in milk production.

Intensive dairy production systems are also prevalent in many parts of the world, particularly in North and Latin America, Western Europe, and increasingly in China, Australia and Eastern Europe. These systems are characterized by large and fully housed dairy herds with high animal densities, high imported feed inputs and external use of labour and other resources to achieve maximum milk yields.



Image 4. Small-scale confinement system in Uganda. Image courtesy of C. Gourley.



Image 5. Intensive grazing system in SE Australia. Image courtesy of C. Gourley.



Image 6. Large-scale confinement system in USA. Image courtesy of C Gourley.

2.1.1 Typical dairy system typologies

Type 1: Small-scale low input systems

These include subsistence-oriented dairy systems, where small numbers of dairy animals (generally less than 4 cows) provide food, income and draught power for rural households, which are milked by hand. This system is widespread in many developing countries of the world.

Common-land pastoral systems, where small herds of dairy animals (generally less than 10 cows) are kept by nomadic or semi-nomadic herders who move their animals in search of pasture and water. This system is present in some arid and semi-arid regions of the world.

Type 2: Medium-scale housing and grazing systems

These include medium-scale mixed grazing and housed systems (generally between 40 and 120 cows), where dairy animals have access to both seasonal grazing and confined housing, including farm-grown forage crops as well as purchased concentrates.

Type 3: Intensive grazing systems

These are medium- to large-scale intensive grazing systems (generally between 200 and 600 cows), have no permanent housing, with managed pastures on private land providing most of the diet for dairy herds.

Type 4; Medium-scale, confinement, cropping systems

These are medium-scale (generally between 150 and 300 cows), including confinement with mixed cropping, with farm-grown crops on private land providing most of the diet for dairy herds.

Type 5: High-intensity confinement, cropping systems

These include large-scale confinement systems and cropping involving dairy animals (generally more than 250 cows) in intensive housing, which are provided with concentrate feeds and forage crops, often as balanced rations. This system is commonly used in developed countries and is characterized by large herds and high levels of mechanization and technology.

Type 6: Landless confinement systems

These are specialized landless systems involving dairy animals (generally > 250 cows, but may be >5000 cows) in confined housing, where concentrate feeds and forage crops are purchased or produced externally. This system is characterized by medium to large herds.

Type 7: Collective farm systems

These are integrated farm systems with dairy animals in confined housing with highly regulated feed and where multiple farms coordinate to jointly produce crops, purchase concentrates, and to manage manure. Individual farms operating as a cooperative mainly have herds ranging from 40 to 100 cows but can include highly intensive operations with > 1000 cows.

2.2 Trends in intensification

Global milk production is projected to increase at a rate of about 2% per year over the next decade, with developing countries expected to experience a greater increase in production and consumption (OEDC-FAO 2022). The increasing demand for dairy products is driven by global population growth, urbanization, rising disposable incomes and changing dietary habits, especially in the Asia-Pacific and African regions. However, milk consumption is also declining in some affluent communities.

In response to increasing demand for dairy products and land constraints, there is a trend towards dairy intensification in many parts of the world. Dairy intensification aims to increase the productivity and efficiency of dairy farming, with higher milk yields per cow and per land area by adopting more intensive production methods, increased use of technology and automation, and the potential for greater profitability for farmers.

Dairy intensification generally means increasing milk production per animal and land area, with more complex and exacting management systems. For dairy animals, intensification typically results from increasing feed intake and optimization of feed conversion efficiency. Increased cow numbers on farms may result in greater reliance on imported feed and more complex feeding systems.

For pasture and forage production, the focus is generally to increase total feed nutrients grown, through improved utilisation of land and greater inputs of water and nutrients, most notably N. Increased animal densities also generally result in higher N (and other nutrient) concentrations in dairy cow excreta, and an increasing proportion of manure deposited in housing or feeding areas requiring collection, storage and land application (Figure 2.1).

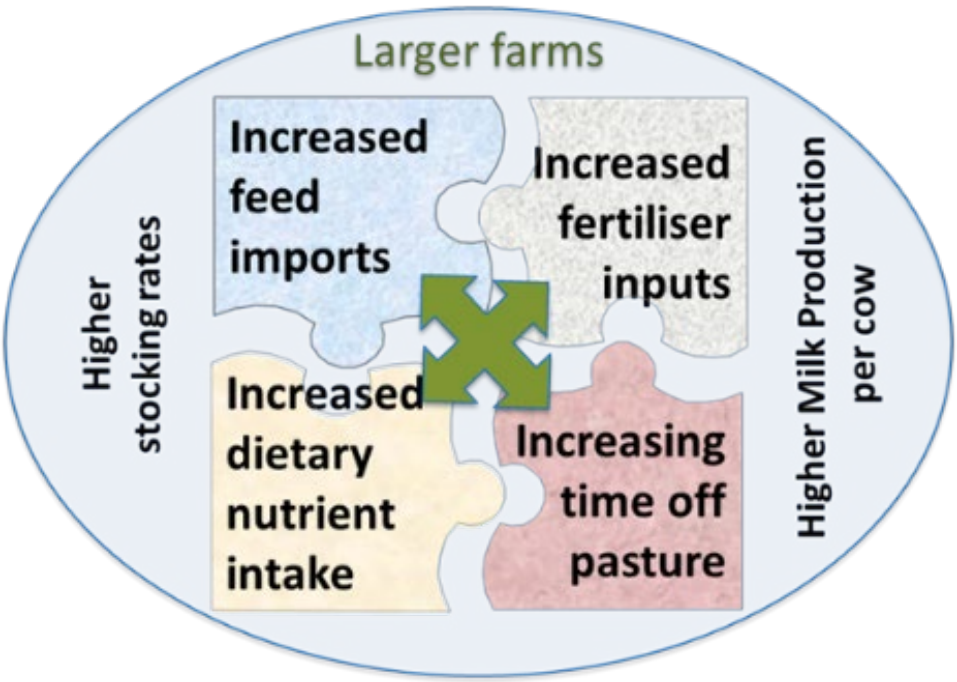


Figure 2.1. Implications of intensifying dairy production systems on nitrogen fluxes within a dairy farm. (Reproduced from Gourley, 2020, with permission from Fertilizer Australia.)

Chapter 3: Nitrogen flows in dairy production systems

3.1 Describing nitrogen cycles and key components

Dairy production systems have significant N requirements to achieve milk production potential compared to other animal production systems and commonly have large N inputs. However, dairy systems are also notably N-leaky, with stepwise inefficiencies as N cycles through the continuum of pasture and crop production, animal and milk production, manure outputs and soil processes (Figure 3.1).

Usually, < 50% of applied fertilizer and manure N is utilized by pasture and crops on dairy farms. A dairy cow typically transforms < 25% of N intake in feed to milk and animal protein, while even well designed and managed manure storage and redistribution systems will retain < 50% of the initial N loads excreted. Consequently, dairy farmers may overcompensate for these inefficiencies by overfeeding N to livestock and over-fertilizing fields, exacerbating the potential for N surplus and N losses to the environment.

Determining N flows, pools and transformations within key production system components of a dairy farm (Figure 3.1) is therefore essential to identify opportunities for improvements in N use and NUE on dairy farms. This is achieved through the quantification of whole-farm and within-farm N efficiency measures, including whole-farm N budgets, feed N use efficiency, manure collection and storage, manure N reuse efficiency, and crop/pasture N uptake efficiency.



Image 7. Milk collection from small-scale farms in Kenya. Image courtesy of N. Hutchings.

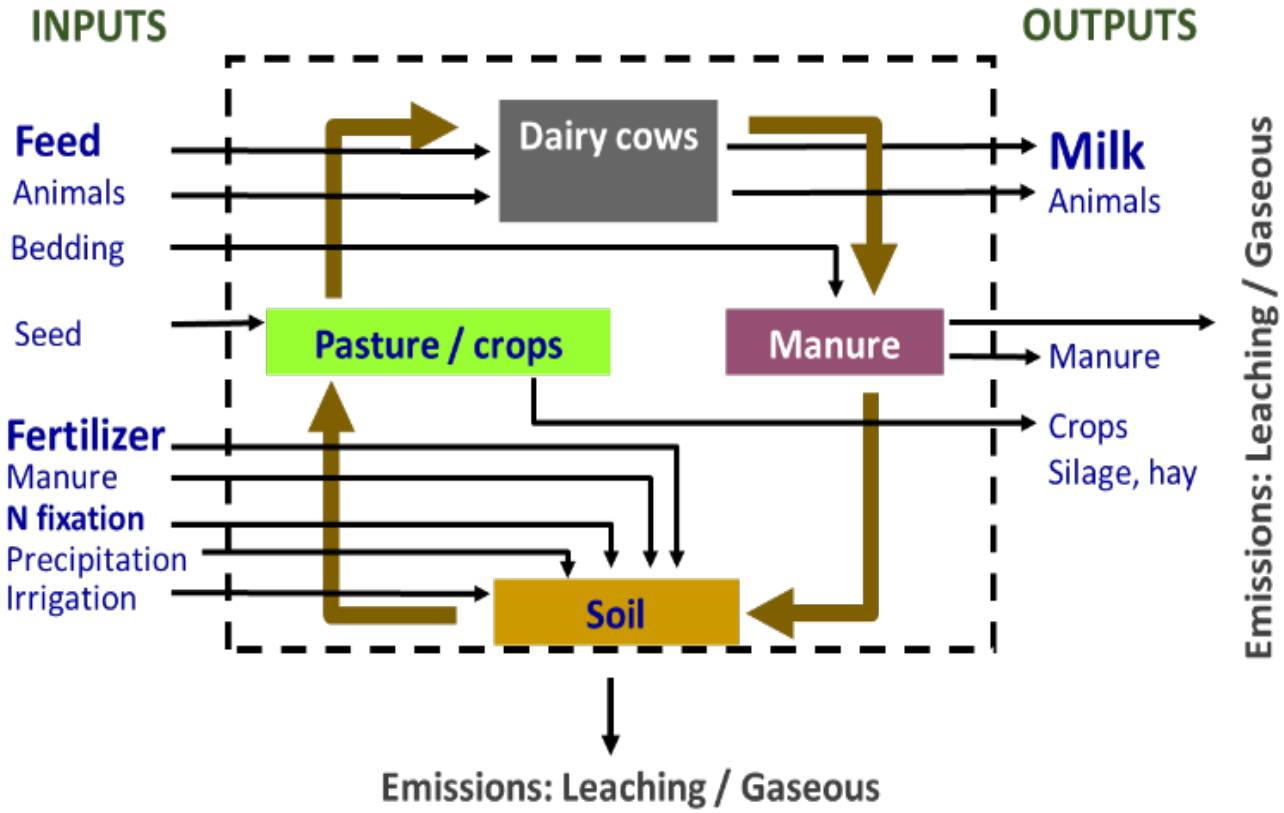


Figure 3.1. Key nitrogen fluxes in and out of a dairy farm and cycling within the farm boundary. (Reproduced from Gourley *et al.*, 2007.)

There are many recognised factors that can result in low NUE on dairy farms. These include:

- Low N output in milk relative to N input
- Low feed conversion into milk
- Excess feed N intakes
- Milking animal longevity
- High N fertilizer applications or low fertilizer N utilization relative to crop or pasture forage yields
- Concentrated or poor redistribution of animal excreted N
- Inadequate manure collection and storage practices
- Inadequate land application practices of stored manure.

3.2 Describing system boundaries

An important part of determining dairy farm N budgets and NUE indicators is ensuring that the land base used for dairy production is well defined. The areas directly contributing to milk production include land used for crop production, grazed and harvested pasture and forages, as well as designated feeding and animal-holding areas. These are the areas where N is cycling through the dairy production system, and where N inputs, utilisation and potential for N losses are occurring.

The sum of these areas directly contributing to milk production (principal milk production area), reported on a per hectare basis, is therefore used when determining nutrient inputs, outputs and net N balance. Whole-farm NUE measures, being ratios, are not affected by assumptions about the land base.

There may also be other land uses within a dairy farm boundary, such as native vegetation, wetland and riparian areas, that do not contribute to milk production and should not be included in the determination of the principal milk production area. However, the management of these additional land areas is increasingly important in providing potential off sets for dairy farm greenhouse gas emissions.

The availability of aerial photography, satellite imagery and geo-referencing of farm and paddock boundaries can assist with defining the principal milk production area (Figure 3.2).

Determining the principal milk production area can be challenging and sometimes lack relevance for certain dairy production systems. For example, low-input dairy systems with tethered animals that rely on harvesting forages from common-lands (i.e., roadsides and unmanaged public land), or nomadic systems utilizing common-land pastures, may have no definable land base. Even highly productive housing systems can be predominately landless, where all feed requirements are imported and all manure is exported. For these systems, more relevant indicators such as feed N use efficiency and manure collection and reuse efficiency are applicable.



Figure 3.2. An aerial photograph with farm and field boundaries is useful for determining the principal milk production area of a dairy farm. (Reproduced from Gourley, 2020, with permission from Fertilizer Australia.)

3.3 Benefits of nitrogen budgets

A whole-farm nitrogen budget accounts for the quantity of N coming onto a farm and the quantity of N leaving the farm in product, usually determined over a 12-month period. A dairy farm nitrogen budget therefore requires information about all key commodities imported and exported for an individual dairy farm, with N flows determined by their mass and corresponding N concentration (Figure 3.3). Nitrogen budgets are generally easy to calculate from readily available and fairly accurate farm-specific data sources.

A standardised whole-farm N budgeting approach has been found to improve farmer knowledge about N flows and potential losses and can influence future fertilizer and manure management decisions. Additionally, whole-farm nitrogen budgets have been used to enable appropriate comparisons and benchmarking between farms, determine industry trends over time due to changing

farm management practices and intensification, and serve as a useful educational, research and policy tool.

Nitrogen efficiency indicators are also beneficial in determining key N flow pathways and opportunities to improve within-farm N cycling. The amount of N in milk and meat, as a proportion of the total N intake by the dairy cow is referred to as NUE_{animal}, and solely N in milk as NUE_{milk}, with animal N surplus providing an estimate of N excreted in urine and dung. Similarly, the amount of N uptake by a crop or pasture, as a proportion of N input as fertilizer, manure, soil N supply or N fixation sources, and NH_3 deposition, is referred to as NUE_{crop} (Figure 3.3).

The integrated nature of whole-farm balances, in addition to climatic and soil conditions, and N management decisions, do not enable environmental N losses via leaching, denitrification or volatilization to be directly estimated. However, N surplus and NUE are useful indicators of the potential environmental pressure poised by N for a specific dairy production system. Further information on other NUE related indicators is provided the INMS Guidance Document on NUE (Lassaletta & Sanz-Cobena, 2026).

Groenestein *et al.* (2019) determined a strong relationship between NUE and NH_3 emissions across all livestock production systems in Europe (i.e., larger NH_3 emission associated with smaller NUE_{animal}), with about 20% of N in feed, lost as NH_3. Differences among European countries were mainly due to contrasting manure management practices. They suggested that disaggregating N emission factors into a diet/animal effect and a manure management effect, in addition to production efficiency (i.e., N surplus milk production^{-1} and NUE), would improve the basis for comparing national NH_3 emission inventories.

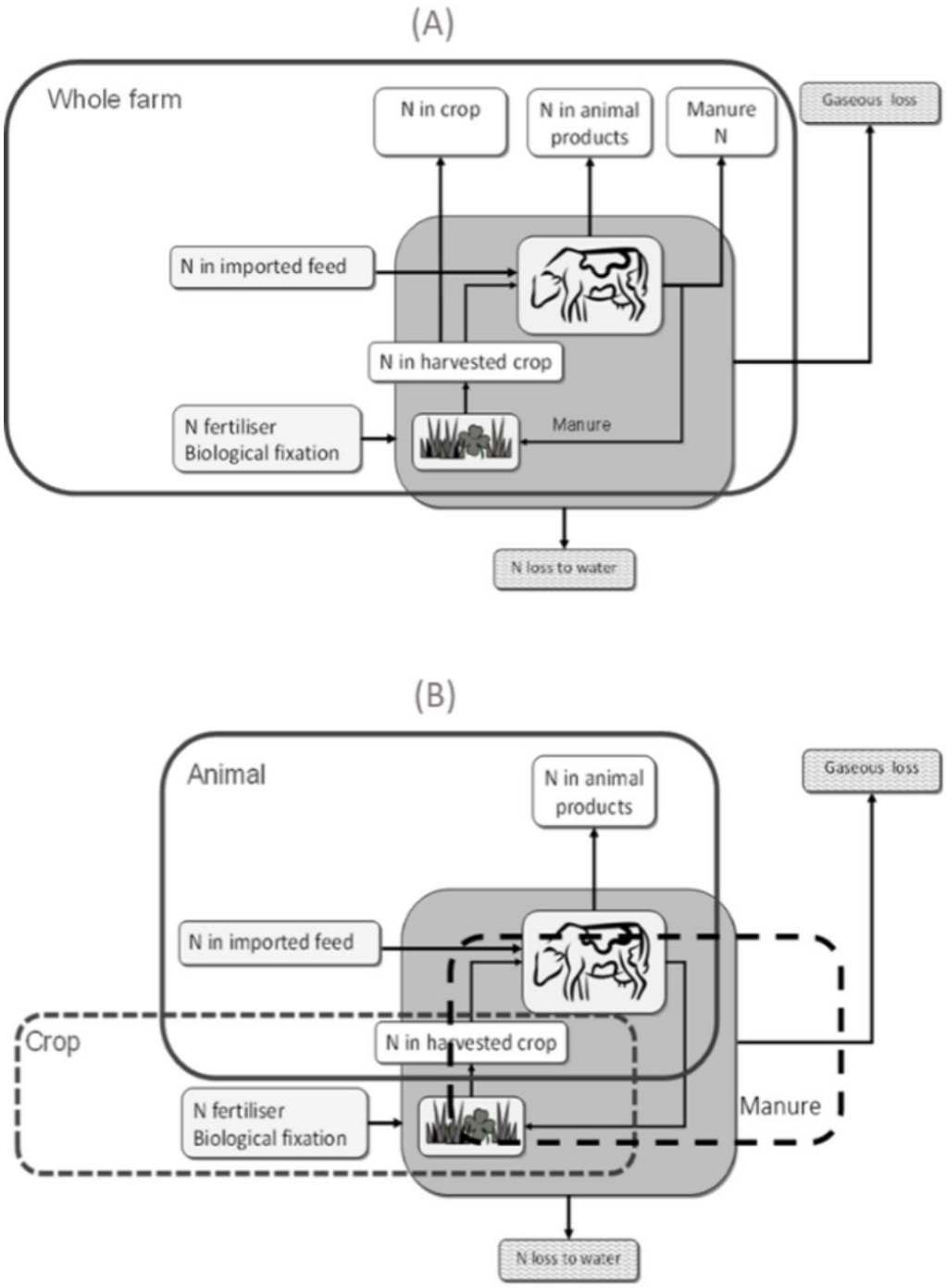


Figure 3.3. Representation of the N inputs and outputs that are typically included in the calculation of (A) Whole farm NUE and N surplus values and (B) component efficiency assessments for Crop/home-grown forage, Animal and Manure reuse. (Reproduced from de Klein *et al.,* 2017.)

Chapter 4: Whole-farm nitrogen use efficiency

Key information

- A dairy farm nitrogen budget requires information about all key commodities imported and exported for an individual dairy farm, with N flows determined by mass or volume and corresponding N concentrations.
- Major commodity N imports generally include mineral fertilizer, feed/fodder, N fixation by legumes, purchased animals, organic soil amendments, and wet and dry N deposition. Lesser contributions may come from seeds, bedding material and irrigation water.
- Major nitrogen exports in commodities include milk, crops, grain, animals, and occasionally manure.
- Whole-farm indicators related to nitrogen use efficiency include:
    - Nitrogen use efficiency (NUE) = [Σ (N outputs) / Σ (N inputs)];
    - N surplus (or deficit) = Σ (N inputs) − Σ (N outputs);
    - N output = Σ (N outputs);
    - Milk production N surplus = N surplus / total litres of milk produced.

4.1 Accounting for nitrogen sources

The whole-farm nitrogen budget approach advocated here follows the procedures described by the EU N Expert Panel (EUNEP 2015) with further definition provided by de Klein *et al.* (2017) and Quemada *et al.* (2020). The nitrogen budget relies on the determination of total N imports and exports (calculated as mass or volume x N concentration of each product considered), standardised to units of kilogram (kg) and determined for a given period (usually a 12-month period that corresponds with the annual production cycle).



Image 8. Fertilizer N applied to pasture. Image courtesy of C Gourley.

Nitrogen inputs entering the farm as inorganic or organic fertilizers or soil amendments, different feed and fodder imports, animal imports, biological N fixation, atmospheric N deposition, seed material, animal bedding, net animal manure imports and N in irrigation water should all be accounted. The amount of imported feed and fodder should be corrected for changes in farm storages.

Nitrogen content of feed and milk should be measured according to internationally recognised analytical methods. Where crude protein (CP) content is provided, total N concentrations in feed (CP/6.25) and milk (CP/6.38) can be calculated as empirical estimates (Powell *et al.* 2015).

Nitrogen outputs from the farm should also include animal products (milk, live and dead animals), feed and fodder, and any other exported N containing materials. Soil N is generally assumed to be in steady state, so is generally not considered in calculations.

Defining the farm system boundary is crucial for the determination of $N_{surplus}$ pressure to the environment. The total hectares contributing to milk production on the farm (principal milk production area) is therefore required. Farm-scale N input and output data should be reported as kg N ha^{-1} $year^{-1}$.



Image 9. Imported grain used in total mixed ration. Image courtesy of C Gourley.



Image 10. Tanker collecting milk for processing. Image courtesy of C Gourley.

4.2 Dealing with externalised nitrogen inputs and outputs

When inputs are produced externally, the apparent NUE of the system typically increases because the costs of N inefficiency are borne by those external production systems. This is especially pertinent in the case of feed imports, where the inefficiencies of N use associated with forage and grain may not be accounted for by the dairy production system. Adjusting N inputs for externalisation can therefore have a significant effect on NUE and N surplus of dairy farms and highlights the need to define and apply adjustment factors where relevant. While integrated farms can be more efficient, in some cases splitting the production system may offer some logistic and environmental advantages.

While it is relatively simple to transport feed to farms, returning manure nutrients to support feed production, especially liquid manure, is more difficult. Manure is a byproduct of milk production and the inclusion of manure N as an export product will result in higher NUE estimates. The net amount of manure N imported is the difference between manure N imported and N exported, corrected for changes in manure in storage. Manure should be considered as either a positive (import – export > 0) or a negative (import – export < 0) N input as part of nitrogen budget calculations.



Image 11. Manure slurry injection system. Image courtesy of C Gourley.

For systems that import feeds, the N required to produce this feed should also be considered as part of N budget calculations, not just the N imported in the feed. De Klein *et al.* (2017) proposed using the applied N required to produce the imported feed, when calculating N inputs for a dairy farm. If the amount of N used to grow the imported feed is not available, Quemada *et al.* (2020) proposed using a relatively large adjustment factor when the feed imported had a low crop NUE, and a low adjustment factor if the imported feed has a high crop NUE or was crop residues and by-products. Alternatively, they proposed a generic adjustment factor for imported feed, assuming a crop NUE of 50%, hence multiplying the net N imported feed N by 2.

These and other potential externalities highlight the need to adequately define the system boundary, and the recognition and importance of considering NUE assessments across interconnected food production systems and the wider economy (e.g., Sutton *et al.*, 2026; Lassaletta and Sanz-Cobeña, 2026).



Image 12. Canola is a common dairy feed supplement. Image courtesy of C Gourley.

4.3 Dealing with uncertainties

Dairy farm nitrogen budgets almost always include inputs such as feed, milk and fertilizer, while other commodities may be excluded when they are not relevant to the farm operations, (i.e., no irrigation, no legumes grown), or make only a relatively small overall contribution (i.e., bedding, atmospheric deposition), while others may rely on the assumption of steady state conditions (i.e., animal numbers and soil N status). However, it is best to include all measurable sources, where possible, as these assumptions are sometimes incorrect, leading to inaccurate estimates of NUE and N surplus.



Image 13. Accurate farm records are required to undertake farm N budgets. Image courtesy of C Gourley.

Another area of bias is the choice of methods used to collect data for the various components. Usually, the mass or volumes of commodities involved in whole-farm budgets is determined by a combination of farm survey methodology and access to farm records for commodities such as forages, concentrates, by-products, fertilizers imported; milk, manure, animal, crop and fodder exports. Discussion and data collection with farmers is key to accurately quantify an N balance. However, the N content of various farm commodities is usually more difficult to define and a tiered approach for estimating N contents and specific N flows is likely to be required.

Reliability of data

Tier 3 data relies on the N content of the farm commodities being considered, based on accurate sampling and chemical analysis, and provides **the most reliable data**.

Tier 2 data utilises local or national **validated information** of N concentrations of commodities.

Tier 1 data relies on more **generic estimates** of N flows from guidance documents.

The use of tier 2 data is appropriate where there is little variation in N concentrations (e.g., mineral fertilizer) or where there is a high level of confidence in the provided concentrations (e.g., N concentrations for livestock and milk phosphorus, P). Tier 2 data are also commonly used for N concentration in grains and forages. However, the use of local reference data is recommended where available, as regional differences in these indirect inputs can be substantial (Rotz *et al.* 2005; Rugoho *et al.* 2016).

Nitrogen fixation by legumes may be an important N input in both pasture and mixed cropping-dairy operations. In pasture systems that include legumes, N input from fixation can vary between 10 - 300 kg N ha^{-1} $year^{-1}$ but is typically less than 50 kg N ha^{-1} $year^{-1}$, particularly when N fertilizer is used (Gourley *et al.* 2012a). The amount of N fixed from the atmosphere by legumes is difficult to measure directly due to spatial and temporal variability and the complexity of measurement techniques. Consequently, N fixation is generally predicted with a tier 2 approach, using recognized relationships between legume type, proportion of legumes in the crop or pasture, yield estimates and adjustments for N fertilizer inputs (Ledgard *et al.* 2003) or tier 1 approach using fixed values or ranges (Rotz *et al.*, 2005).

Some of the inputs from legume N may be realized in the year or years after the crop is grown. Some of the apparent N benefits of legumes may be due to improvement in crop growth based on other benefits.

Where N contributions are both difficult to directly measure and where the contribution is likely to be small relative to other components, as is usually the case for wet and dry atmospheric N deposition in intensive systems and N in irrigation water, a tier 1 approach is most common.

Estimates of uncertainty (coefficient of variation) for N inputs and outputs will vary (Oenema *et al.* 2003), but are generally small and usually less than 10% for the major N imports and exports (i.e., feed, fertilizer, milk, animals), while there can be a high degree of uncertainty attributed to N fixation and manure. As the variance estimates are integrated for the various forms of N imports and exports, the collective uncertainty for most N budgets is reduced. For example, Gourley *et al.* (2012a) found that the uncertainty of N surplus estimates for 41 mostly grazing-based dairy farms ranged between 2 and 11%, with a median uncertainty of only 4%.

4.4 Whole-farm nitrogen budget calculations

Whole-farm N budget indicators should be calculated at the farm-scale on an annual basis, and should include:

- Nitrogen use efficiency (NUE %) = [Σ (N outputs) / Σ (N inputs)] x 100 [1]
- N surplus (kg) = Σ (N inputs) – Σ (N outputs) [2]
- N output (kg) = Σ (N outputs) [3]
- Milk production N surplus (g/l) = N surplus / total litres of milk produced [4]

For an individual dairy farm, the reported N budget outcomes therefore include:

- NUE, a measure of N resource efficiency (since whole-farm NUE is a ratio, it is not influenced by the land area of the farm);
- N surplus, a measure of N loss pressure to the environment (assuming no changes in soil N);
- N output, a measure which reflects the intensity of N export in product; and
- Milk production N surplus (N surplus divided by litres of milk produced).

This latter metric is akin to the partial productivity measures used in production economics and recognises that dairy farming aims to increase the profitability of milk production while also ensuring environmental quality. These aims may be better served by more intensive, highly productive farms on a more limited area, more distant from valued environmental assets.

4.5 Interpreting nitrogen budget outcomes

There are natural losses of N in any ecological system, and animal production systems are recognised as being particularly N-leaky. Defining a NUE target for an agricultural system is likely to be situation and impact dependent (Norton *et al.*, 2015). Comparisons between systems can therefore be very informative, while differences within any system should be examined to determine the most effective measures that can increase or decrease NUE.

In a general sense, very low NUE indicates a greater risk of N losses and negative environmental impacts, while a very high NUE indicates more N is likely to be removed than replaced, decreasing soil N supply and degrading soil organic reserves. However, a high NUE does not necessarily imply a low risk of N loss. For some highly intensive systems, NUE can be high, but the quantity of N loss per land unit may still be considerable. In this regard, estimation of N surplus (inputs – outputs) is an important complementary indicator. Targets for N performance indicators should therefore be aiming for high utilisation of N input whilst also minimising the quantity of potential N loss while aiming to optimize productivity.

Dairy production systems will have different NUE and N surplus targets than cropping production systems because of the integrated flows of N, relatively low animal utilization of N intakes, inherent losses of N from excreted manure, and required N mineralization in soil to release organically bound N from manure and crops. Moreover, the intensity of the dairy system should also define a range of indicatively feasible NUE and N surplus targets appropriate for each system (Table 4.1). For any particular system, opportunities may exist for moving to higher values of NUE and lower values of N surplus within the range.

Table 4.1. Indicative target range for NUE and N surplus as a function of farming system and dairy production intensity. Livestock unit (LSU) equivalent to one adult dairy cow producing 3000 kg of milk annually. (Modified from Bittman *et al.*, 2014.)

Farming systems	System categories	NUE (%)	Area-based N surplus, (kg/ ha)	Milk production N surplus, (g/ l)	Comments
Specialized cropping systems	Arable crops	60 - 90	0 - 50	Not applicable	Cereals have higher NUE. Root crops have lower NUE.
Traditional low-input dairy system	Very low intensity (<0.5 LSU/ha)	20 - 30	25 - 50	8 - 12	Very small herds, low quality and quantity of feed available. Low milk production per animal. Agronomic use of manure low.
Grassland-based dairy system	Low intensity (1 LSU/ha)	30 - 50	100 - 200	8 - 12	High milk yield, high NUE. Low stocking density, low N surplus.
Mixed crop-dairy system	Medium intensity (1-2 LSU/ha)	40 - 60	100 - 150	6 - 10	High milk yield per animal. Concentrate feeding.
Landless dairy systems	High intensity (Fully housed - essentially no land).	80 - 90	Not applicable	Not applicable	N output via milk, animals and manure ~equals N input in imported feed. N surplus is largely gaseous N losses from housing and storages.

NUE outcomes are generally interpreted using a two-dimensional N input - output framework that combines different N budget indicators (Figure 4.1). This framework considers the minimum amount of N input required for production, the maximum N surplus that is environmentally acceptable, the minimum NUE level to avoid wasting N and the maximum NUE to avoid soil mining. Once goals are set for these parameters, the calculated N inputs and N outputs for a specific dairy farm can be referenced within the framework, to assess whether desired outcomes are achieved.

Building on the NUE framework (Figure 4.1), Quemada *et al.* (2020) provided associated guidance for hypothetical farms on N management pathways to achieve an improved NUE outcome (Figure 4.2). For example, farms with high potential maximum yields (Figure 4.2; Curve I) should increase or decrease external N inputs to reach the desired NUE (Farms B and C, respectively). Farms with a lower yield potential (Figure 4.2; Curve II) could sustainably intensify by optimising production factors other than N, and then increase of reduce N inputs (Farms D and E respectively). Finally, farms where N outputs are larger than N inputs should increase their N inputs to avoid mining soil N (Farm F).

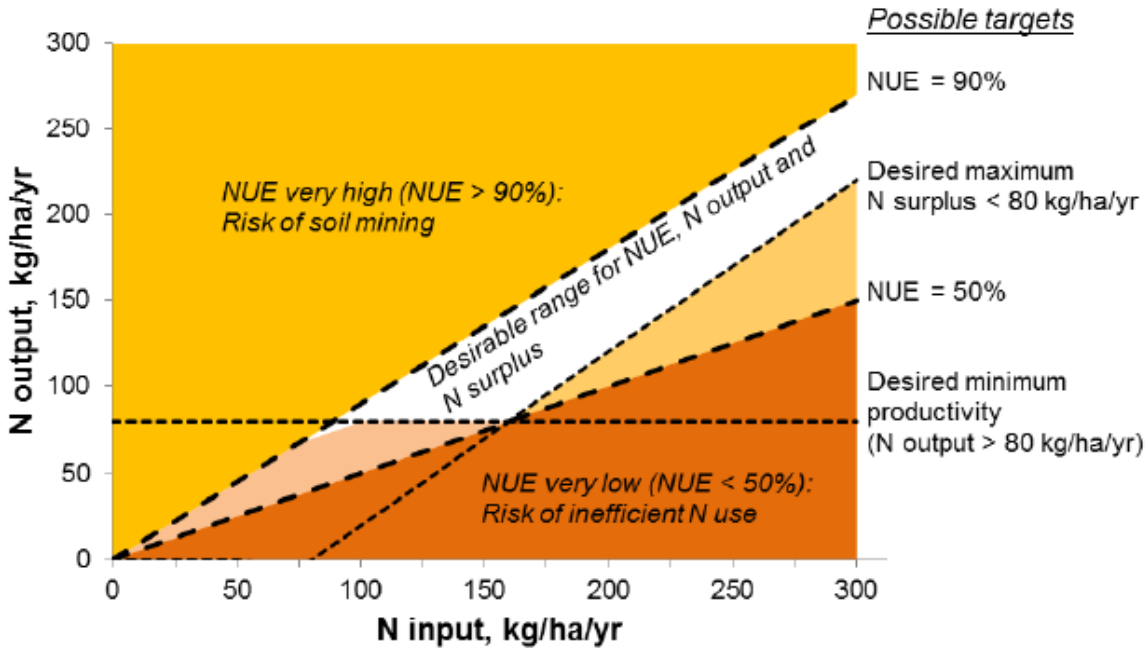


Figure 4.1. Conceptual NUE framework developed by the EU Nitrogen Expert Panel (2015), providing reference values and interpretation criteria, which may vary according to context (soil, climate, crop and animal products and acceptable N losses). The slope of the diagonal wedge represents a range of desired NUE values between 50% and 90%; lower values are likely to exacerbate N pollution and higher values risk mining of soil N stocks. The horizontal line is a desired minimum level of productivity for the example system. The additional diagonal line represents a limit related to maximum N surplus to avoid substantial pollution losses. The combined criteria serve to identify the most desirable range of outcomes, represented by the trapezoid shaped part of the Figure. (Reproduced from EU Nitrogen Expert Panel, 2015.)

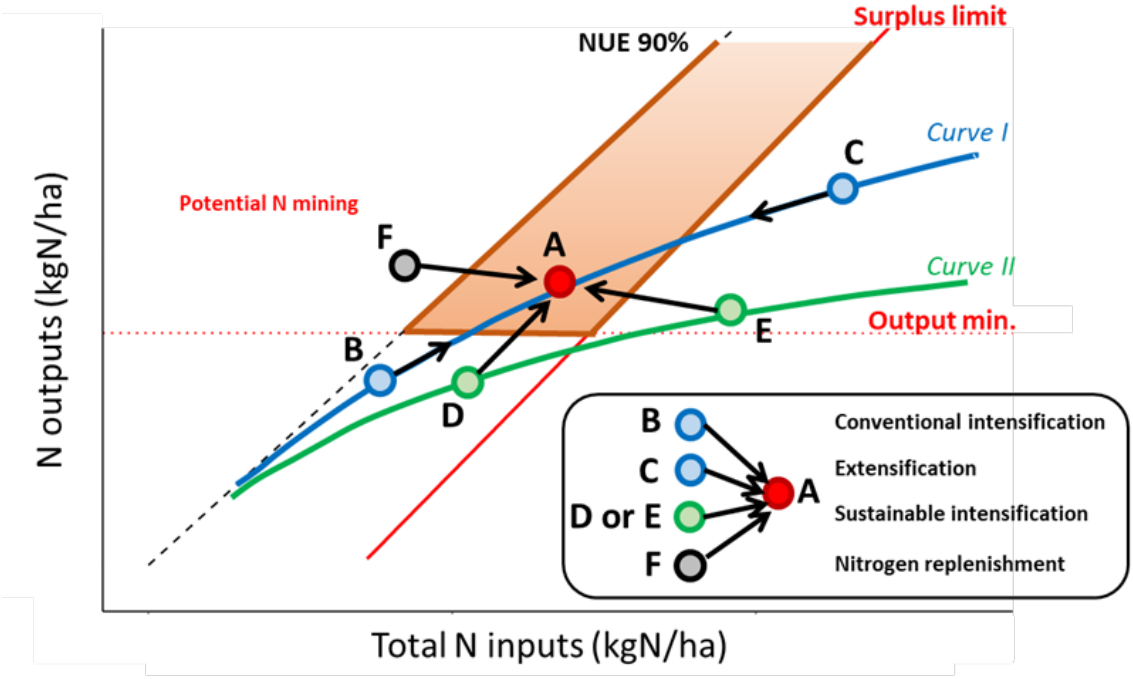


Figure 4.2. Conceptual framework proposed by Quemada *et al.* 2020, for farms to achieve an optimum NUE operating environment (point A in shaded area). Curve I represent farms with a higher potential maximum yield (farms B and C) than those on Curve II (Farms D and E). Farm B has N limitation with production and NUE benefits from increased N inputs; Farm C has N inputs in excess of production requirements. Farms D and E are yield limited by factors other than N limiting optimum production, as well as requiring N input refinement. Farm F requires increasing N inputs to satisfy N removal. (Reproduced from Quemada *et al.* 2019, CC BY 4.0.)

Chapter 5: Dairy cow nitrogen use efficiency

Key information

- Determining feed N intakes and NUE_{milk} is an important first step in assessing the utility of N intakes for production.
- The system milk boundary is focused on the lactating cow, with milk production influenced by feed quality and quantity, breed, animal age and size, number of lactations, method of milking, and animal health and welfare.
- Accurate data to determine feed intake and N content may be limited, especially in low-input and traditional dairy systems and those where feed intake is dominated by grazing.
- Dairy farm manure N use efficiency indicators include:
  - NUE_{Milk} % = 100 * (Milk N (g cow^{-1} day^{-1}) / Σ Feed N intake (g cow^{-1} day^{-1})
  - Manure N Excreted (g cow^{-1} day^{-1}) = [Σ Feed N intake (g cow^{-1} day^{-1}) - Milk N (g cow^{-1} day^{-1})]

5.1 Variations in feed intakes and milk production

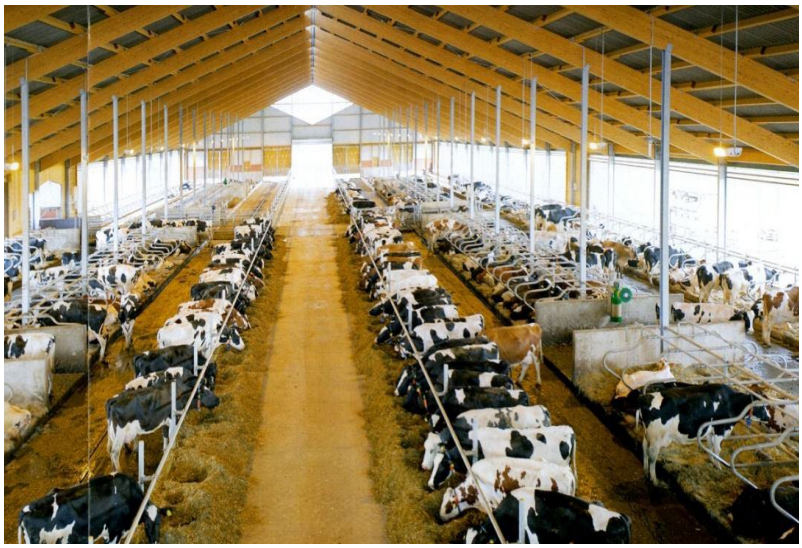
The average dry matter (DM) and N intake for lactating dairy cows globally is estimated at 21 kg DM and 477 g N per day, respectively, with lower average intakes in Africa and Asia, and higher intakes in Europe, North America and Oceania (Powell *et al.* 2013). Average milk production per cow is generally highest in Europe and North America, largely associated with larger herds and controlled and balanced diets, and good cow genetics (dairy system typologies 3-7). Where small-scale and traditional systems dominate, milk production per cow ranges from approximately one-third (Asia and Central and South America) to one-eighth (Africa) of milk production in industrial dairy production systems (OECD-FAO 2022).

Establishing the relationship between feed nutrients and milk production is a logical first step in determining nutrient efficiencies within a farm-system. Determining N intakes and milk N and manure N excreted is more routine in larger-scale confinement-based systems due to the relative ease in determining and measuring dietary intakes. By contrast, measuring pasture or forage intake in grazing systems, or low input mixed grazing and housed dairy systems, is more challenging due to the interactions of the grazing animal and feed sources (pasture and supplements).



Image 15. Collected forage from common lands. Image courtesy of K Dahal.

In intensive grazing-based systems (i.e., typologies 3 and 4; Chapter 2) estimates of DM intake are commonly based on field-scale pasture/forage removal, or the use of models which use a 'back-calculation' approach to estimate pasture intake from net energy requirements to produce milk, accounting for additional energy demands such as pregnancy, maintenance, grazing and walking (Aarons *et al.* 2020).



In large-scale and specialised dairy production systems, particularly in North America, Europe and Japan, the monitoring of milk urea nitrogen (MUN) can serve as a useful indicator of feed N management practices, as it reflects the efficiency with which dietary nitrogen is used by cows. By monitoring MUN levels in milk, dairy producers can avoid excessive N intakes and reduce the amount of N excreted.

Image 16. Large-scale free stall barn. Image courtesy of K Groenestein.

Powell *et al.* (2013) proposed three N intake efficiency measures for lactating cows:

i. NUE_{milk}: The proportion of N intake by a lactating cow that is excreted in milk,
ii. $NUE_{edible\ protein}$: The proportion of N intake by a lactating cow that is excreted in milk plus N sequestered in animal meat, and
iii. NUE_{herd}: The proportion of N intake by a lactating cow that is excreted in milk plus N sequestered in the animal.

In general, however, NUE-milk is the most used N intake efficiency indicator, representing the primary purpose of feeding lactating cows, and accounting for most of the N output in agricultural product.



Image 17. Milking parlour with automated data collection. Image courtesy of C Gourley.

5.2 Calculating NUE_{milk}

The efficiency of conversion of feed N intake to excreted milk N (NUE – Milk) is calculated as:

$$NUE_{milk}\ \% = 100 * (\text{Milk N (g cow}^{-1}\ \text{day}^{-1}) / \Sigma\ \text{Feed N intake (g cow}^{-1}\ \text{day}^{-1}) \quad [5]$$

Where total feed N intake is determined by multiplying the N concentration of each feed component (feed CP divided by the empirical conversion of 6.25; see Section 4.1) with its estimated or measured DM intake and then summing the N intake of all feeds; and milk N secreted, calculated by multiplying daily milk produced by the concentrations of N in a composite milk sample (milk CP divided by 6.38, See Section 4.1).



Image 18. Maize silage storage for large-scale total mixed ration (TMR) systems. Image courtesy of C Gourley.

However, a hybrid tiered approach for determining NUE_{milk} is likely to be required, based on the data available to determine N intakes and milk N content.

- A tier 3 data approach is preferable, based on accurate sampling and chemical analysis of the component of the dairy cow diet.
- A tier 2 data approach uses local or national information on N content of feed and milk.
- A tier 1 data approach relies on a simplified and generic relationship between milk production and NUE - Milk from guidance documents (Figure 5.1).

Similarly, the N excreted in manure by lactating dairy cows (assuming N retention by the lactating cow is negligible) can be calculated as:

$$\text{Manure N Excreted (g cow}^{-1}\ \text{day}^{-1}) = [\Sigma\ \text{Feed N intake (g cow}^{-1}\ \text{day}^{-1}) - \text{Milk N (g cow}^{-1}\ \text{day}^{-1})] \quad [6].$$



Image 19. Calculating feed components. Image courtesy of N Hutchings.

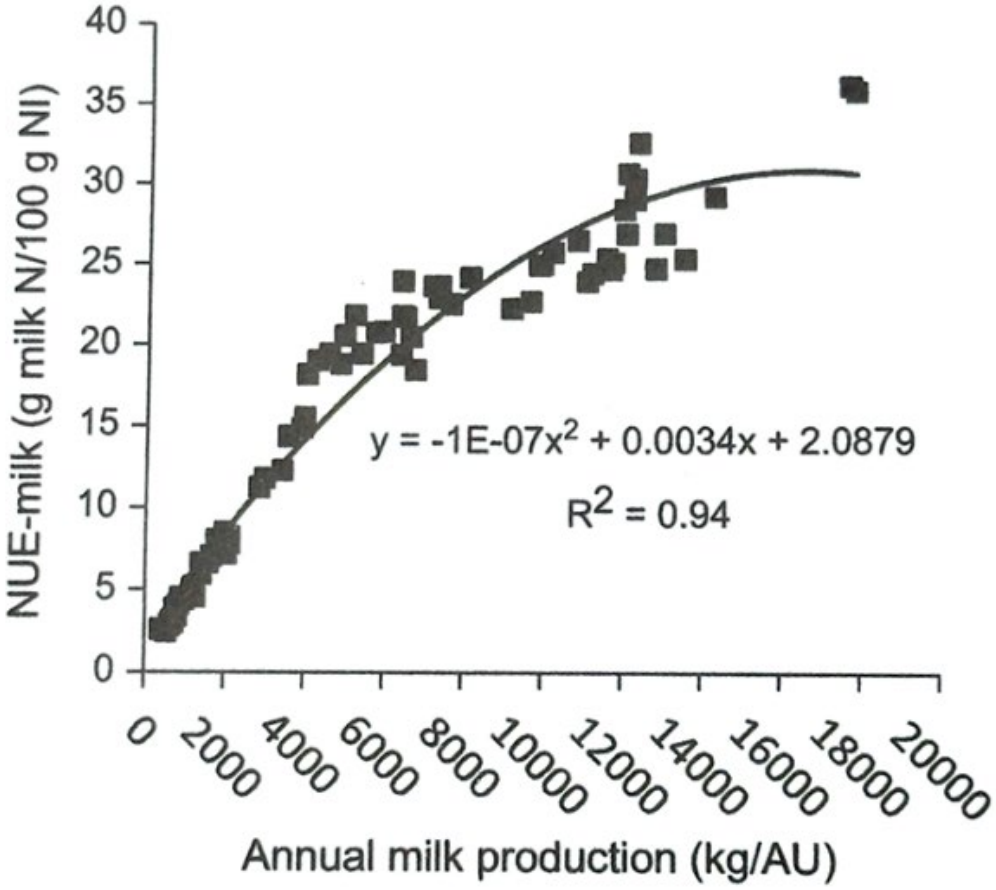


Figure 5.1. Relationship between annual milk production and NUE_{milk} for a diversity of global milk production systems. NI is N Intake; Au is animal unit. Milk is fat and protein corrected. (Reprinted from Powell *et al.* 2013, with permission from Elsevier.)

5.3 Interpreting NUE_{milk}

The utilization of N intake into milk N is relatively low. Powell *et al.* (2015) estimated that the global average NUE_{milk} is 16%, with substantial differences reported both between and within regions. These differences are driven by contrasting diet quality, CP%, protein quality and DM intakes, milk production, animal breed, and production systems and practices.

NUE_{milk} is generally highest in large-scale and highly specialised production systems (20-30%), such as those which are dominant in Europe and North America, and landless systems in Asia. By contrast, NUE_{milk} is generally much lower (5-15%) in small-scale traditional systems found in Africa and South-Asia (Powell *et al.* 2015).

Indicative target ranges for NUE_{milk} (%) for a range of dairy production systems are provided in Table 5.1. The high variability of NUE_{milk} among farms in a region or typology suggests that there are substantial opportunities to improve cow nutrition and husbandry through training, education and supporting services like feed formulators and veterinarians, resulting in improved overall milk yields and recycling of manure N. In confinement operations there is better control of feed quantity and nutrient concentrations throughout the year, which in turn determines milk production and the quantity and nutrient concentrations in manure. This is more difficult when dairy animals freely graze, and when the CP concentrations of grazed pasture and forages vary due to climatic and seasonal conditions.

Table 5.1. Indicative target ranges for NUE_{milk} (%) as a function of farming system and dairy production intensity.

Dairy systems	System intensity	Very low NUE_{milk}	Low NUE_{milk}	Medium NUE_{milk}	High NUE_{milk}	Comments
Traditional low input. Confined >80% of time	Very low	>5	5-10	10 - 15	>15	Very small herds, low feed quality. Low milk production. Agronomic use of manure low.
Grassland-pasture based. Confined <10% of time	Low (1 LSU/ha)	>10	10-15	15 - 20	>20	Medium milk yields. Low stocking density, low N surplus. Presence of legumes.
Grazing + concentrates Confined <20%	Medium (1-2 LSU/ha)	>15	15-20	20 - 25	>25	High milk yield. Low stocking density, moderate N surplus. Presence of legumes.
Mixed cropping Confined >40% of time	Medium (1-2 LSU/ha)	>20	20-25	25 - 35	>35	High milk yield. Concentrate feeding. Moderate N surplus
Mixed crop- Confined >90% of time	High (2-3 LSU/ha)	>20	20-25	25 - 35	>35	High milk yield, high N surplus. Concentrate feeding.
Landless dairy systems Confined ~100% of time	High (Fully housed - essentially landless).	>20	20-25	25 - 35	>35	High N inputs, total manure export, high milk yield. No N surplus production system.

Chapter 6: Manure nitrogen re-use efficiency

Key information

- Generally, less than 25% of N consumed by dairy cows is returned in milk, resulting in large quantities of N-rich urine and dung manure excreted.
- Managing manure (a mix of urine and dung, often with animal bedding included) is an essential aspect of recycling N and improving NUE on dairy farms.
- Dairy farm manure N use efficiency indicators include:
    - Manure N generated on farm per ha of dairy production land base;
    - Manure N collected as proportion of manure N generated;
    - Manure N animal deposited to pastures as proportion of manure N generated;
    - Manure N exported as proportion of manure N generated.
- Plant N availability from manure requires efficiency factors corresponding to manure N fractions and land application practices.

6.1 Manure sources and use

Manure management is an essential part of nearly all dairy farm operations and vital for nutrient management planning. It provides valuable nutrients and organic matter that boost crop and pasture production, but also can be used as a source of energy.

Cows partition excreted N in urine and dung. Urinary N is primarily present as urea, while N in dung is generally evenly divided between inorganic (ammonium, nitrate and nitrite) and organic forms. The N content of urine and dung is influenced by the breed, age and size of cows, cow diet (especially CP content), water intake and milk production, with higher N intakes by cows resulting in a higher proportion of excreted N in urine (Nennich *et al.* 2005).



Image 20. Dried and stored dung pads in India for use as fuel. Image courtesy of C Gourley.

Manure (combined urine and dung, which may also contain bedding material) collected from confined or tethered animals in low-input systems may be used as a fertilizer (for a broad range of crops and vegetables for both human and alternative animal consumption), as a feedstock for small-scale bio-methane production (which should include nutrient recovery, see Amon *et al.*, 2022), or as a building material or fuel for domestic cooking. In these two latter cases, manure N is deemed lost from the dairy

system, but not necessarily lost to the environment. While burning manure tends to release N to the air, either as N_2 or N_r air pollution, biogas production holds the opportunity to prepare a range of possible nutrient products for use in farming systems.

The collection of manure in grazing-based dairy systems largely occurs from permanent infrastructure and adjacent holding yards where cows are milked. Grazing and mixed cropping-animal systems may also have dedicated feeding areas and housing facilities, used in adverse seasonal conditions.

Tie-stall barns, where manure is collected in a gutter behind the cows, are common in more traditional dairy systems having less than 100 cows. This manure is solid or semisolid and may be stored or regularly removed and applied. In some systems there is opportunity to collect and cover urine separately, which reduces ammonia emissions to air and improves NUE (see Amon *et al.*, 2022).



Image 21. Scraped manure from outdoor yards, WI, USA. Image courtesy of C Gourley.

Larger herds in more intensive systems are usually housed in free-stall barns, where cows move freely between stalls, and where sand, separated manure solids or covered mattresses are used as bedding material. In these housed systems, liquid slurry is scraped or washed from the concrete alleys and is typically stored in an open earthen or cement-lined pit or above ground steel tank, that is emptied two or more times per year, and machine-applied to fields to meet crop nutrient demands.

6.2 Dung and urine collection for re-use

Dairy cattle deposit dung and urine in various locations, depending on the farm system and herd management practices. Farmers generally collect manure from shelters, barns, milking parlours and holding yards, while manure deposited to pasture, as well as some unproductive areas (laneways, exercise yards, common lands) is usually uncollected. Seasonal conditions can also influence where cows and located and manure management practices.

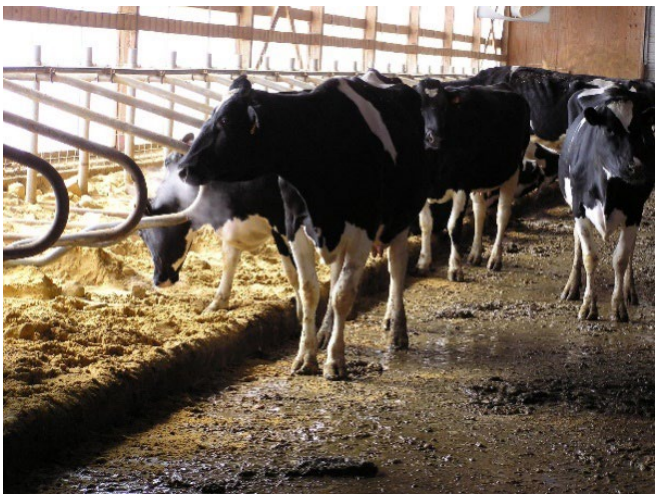


Image 22. Free stall barn with sand bedding and scraped laneway, WI, USA. Image courtesy of C Gourley.

In many housed livestock systems, a mix of dung, urine and bedding is collected, often termed 'farm yard manure'. Although urine is less often collected separately, this can have several advantages to reduce ammonia emissions and increase NUE. Although N is urine is mainly excreted in the form of urea, this rapidly hydrolyzes to ammonium, hence risking ammonia emission, but readily usable by plants where emissions can be prevented (Bittman *et al.*, 2014).

Knowing where, when and how much dung and urine is deposited in specific locations is necessary for determining manure storage requirements, nutrient loads and land requirements for manure application. It is also important in determining the amount of dung and urine not collected and the potential accumulation areas and N 'hotspots' exacerbating environmental N losses from dairy farms.

In dairy systems, quantifying manure deposition should focus on:

- The total amount of manure generated by the entire herd,
- Manure routinely collected when cows are in confined spaces,
- Manure directly deposited to grazed pastures, and
- Manure deposited to non-productive areas with no collection.

The amount of dung and urine deposited in specific locations is generally determined by estimating the relative amount of time cows spend in various farm locations, the number of animals and the average daily N excreted per animal. Calculations usually assume that manure generation is evenly distributed throughout a 24-hour period.

Powell *et al.* (2005) proposed manure collection efficiency (defined here as ManCE) as a general indicator for manure N recycling (including both urine and dung):

$$\text{ManCE (\%)} = (\text{Manure collected} / \text{Manure Excreted}) * 100 \quad [7]$$

Seasonal conditions often result in changes in management, with cows grazing pasture or within exercise yards, where dung and urine are excreted but not collected. On an annual basis, ManCE can therefore be further refined to account for the actual manure available for collection in each season, based on (estimated) fractions of time cows spent in areas where manure goes uncollected:

$$\text{ManCollect\%} = (1 - [(Dsp)(Ysp) + (Ds)(Ys) + (Df)(Yf) + (Dw)(Yw)]) * 100 \quad [8]$$

where the term ManCollect represents the predicted proportion of manure available for collection; D represents time spent daily in outside areas where manure is not collected (fractional days), for different seasons (spring, sp; summer, s; fall, f; and winter, w) and Y represents a season's length (fractional year), as recorded / reported.

In contrast to systems where cows are largely confined, dairy cows in grazing-based systems deposit most of their manure directly on pastures. Consequently, manure deposition and collection efficiency measures for grazing operations need to recognize the benefits and risks of non-collected manure directly deposited unevenly to pastures, while also assessing the potential inefficiencies of manure deposited to non-productive areas where manure is not collected (Table 6.2).

The proportion of manure deposited on pasture (as both dung and urine) by grazing animals, can be determined as:

$$\text{ManPasture\%} = [(PASTsp)(Ysp) + (PASTs)(Ys) + (PASTf)(Yf) + (PASTw)(Yw)] *100 \quad [9]$$

Where ManPasture represents the proportion of manure excreted directly onto pasture by grazing cows; PAST represents time spent daily grazing (fractional days) for different seasons, as described above.

Similarly, the proportion of manure within a grazing system which is deposited in areas with routine collection (i.e., feed pads, holding yards, milking parlour), can be calculated, based on time spent in these designated areas:

$$ManGrazeCollect\% = [(GrazeCsp)(Ysp) + (GrazeCs)(Ys) + (GrazeCf)(Yf) + (GrazeCw)(Yw)] * 100 \quad [10]$$

where ManGrazeCollect represents the proportion of manure excreted on areas other than pasture which is available for collection. GrazeC represents time spent daily (fractional days) when cows are on non-pasture surfaces but where manure is collected, for different seasons as described above.

High manure loads, particularly in non-productive areas on a farm with no associated manure collection (NonPROD) may pose a significant risk of nutrient loss (Gourley *et al.*, 2012; Powell *et al.*, 2005). On an annual basis, the proportion of manure deposited in NonPROD areas, can be determined as:

$$ManWaste\% = [(NonPRODsp)(Ysp) + (NonPRODs)(Ys) + (NonPRODf)(Yf) + (NonPRODw)(Yw)] * 100 \quad [11]$$

where ManWaste is the proportion of manure with no reuse, NonPROD represents time spent daily (fractional days) on non-productive areas with no manure collection, determined for different seasons as described above.

Recognizing differences in the location and duration of cows within a dairy farm, indicative target ranges for manure collection, distribution and potential reuse are provided in Table 6.1.

Table 6.1. Indicative target ranges for manure collection, distribution and potential reuse as a function of farming system and dairy production intensity.

Dairy systems	System intensity	Man-Collect %	Man-Pasture %	Man-Graze-Collect %	Man-Waste %	Comments
Traditional low input. Confinement >80%	Very low	80 - 90	Not relevant	Not relevant	10 - 20*	Very small herds, low feed quality. Low milk production. Agronomic use of manure low.
Grassland-pasture based Confinement <10%	Low (1 LSU/ha)	Not relevant	85 - 93	5 - 10	2 - 5	Medium milk yields. Low stocking density, low N surplus. Presence of legumes.
Grazing + concentrates Confinement <20%	Medium (1-2 LSU/ha)	Not relevant	70 - 83	15 - 25	2 - 5	High milk yield. Low stocking density, moderate N surplus. Presence of legumes.
Mixed cropping Confinement >40%	Medium (1-2 LSU/ha)		30 - 43	55 - 65	2 - 5	High milk yield. Concentrate feeding. Moderate N surplus
Mixed crop- Confinement >90%	High (2-3 LSU/ha)	90 - 95	Not relevant	Not relevant	5 - 10	High milk yield, high N surplus. Concentrate feeding.
Landless dairy systems Confinement ~100%	High (Fully housed - essentially landless).	95 - 98	Not relevant	Not relevant	2 - 5	High N inputs, total manure export, high milk yield. No N surplus production system.

Man is Manure including excreted urine and dung; Man-collect is collected manure; Man-pasture is % manure deposited to pasture; Man-graze-collect is % manure excreted on areas other than pasture which is available for collection. Man-waste is % manure wasted, i.e., not collected for later processing/re-use or returned directly to pasture. *Use of collected manure as fuel and building material should also be included as Manure waste since the nitrogen is mainly converted to N_2 in burning or lost as N_r emissions to air.

6.3 Nitrogen losses from dung and urine

The type and size of manure storage systems are influenced by herd size, housing type, proportion of dung and urine collected, availability of labour and mechanization, purpose of manure use, crop type and demand, land available, and soil characteristics and water availability.

In traditional low input small holder farms with only a few animals, manure containing a mix of dung, urine and added bedding (such as straw) is scraped and collected manually, then dried and stored. With larger cow numbers (>20 cows), collected manure is generally stored in earthen pits or open composting manure piles. In some cases, urine may be collected separately.

In mixed cropping and dairy systems with larger herds (~200 cows or more) manure is usually mechanically scrapped and stored as slurry in tanks or sealed storage dams, which may be covered. Wash water is also commonly used to clean concrete surfaces, resulting in higher volumes of low dry matter (effluent) water, requiring larger storages.

Intensive grazing-based dairy systems have a much smaller proportion of manure requiring storage (because most excreta is returned directly to pasture), with manure collection generally occurring from animal holding yards and the milk parlour, and perhaps designated confined feeding areas. Manure is generally collected in liquid form using pressure or flood-wash systems and the effluent is stored in a series of open ponds.

Large-scale dairy systems, especially where water is in short supply, are increasingly managing dairy slurry manure through liquid-solid separation (Amon *et al.*, 2022), which includes the recycling of wash water, large liquid storages of effluent with low solid contents and solid manure composting stockpiles; all these increase management, labour, electricity and maintenance costs but improve the usability of manure nutrients.

Losses of N from excreted dairy manure generally range from 20-40% but can exceed 50% (Chadwick *et al.* 2011), with the largest loss pathway usually as ammonia (Bittman *et al.* 2014).



Image 23. Covered solid manure, Kenya. Image courtesy of N Hutchings.



Image 24. Scaped manure from free stall barn, NSW, Australia. Image courtesy of C Gourley.



Image 25. Mechanical separation of manure, Southeastern Australia. Image courtesy of C Gourley.

Manure N losses are influenced by many physical, chemical and biological processes as well as farm management practices (Figure 6.1) including moisture content, gaseous exchange, crust formation, oxygen supply, pH conditions, temperature and types of facilities.

Notably, the high pH of cow manure (generally > 7) promotes the chemical conversion of ammonium (NH_4^+) to ammonia (NH_3) resulting in significant NH_3 emissions to the atmosphere, which continue in open storages. Additionally, the rapid transformation of urea N to NH_4^+ on hard surfaces, exacerbated by the mixing of urine and dung and the prevalence of the urease enzyme, exacerbating NH_3 volatilization losses. There are benefits of immediate segregation and covered storage of urine (Amon *et al.*, 2022).



Image 26. Covered slurry storage, Denmark. Image courtesy of C Gourley.

Reducing gas exchange using containment systems with air-tight roof or tent structures, reduced surface areas, or floating covers are recommended to reduce gas exchange (Bittman *et al.* 2014). Physical barriers may result in anaerobic conditions, increasing methane (CH_4) emissions, but providing an opportunity for biogas collection. The potential risk to humans and cows from elevated concentrations of NH_3 and other gases in air-tight structures need to also be considered.

The addition of inorganic or organic acids can also be used to increase the retention of NH_4^+, at least in short-term storage prior to land application, or added to slurry during land application (Amon *et al.*, 2022). In order to ensure the benefits of reducing N losses by reducing pH or through containment infrastructure land application of stored manure should follow best practice. For high pH slurries, low-emission band-spreading or injection is appropriate (Misselbrook *et al.*, 2022), while the amounts of fertilizer used should be adjusted to account for reduced N losses (Oenema *et al.*, 2022).

Composting and medium to long-term storage of manure stockpiles will reduce moisture content and overall volume but will further reduce N content and availability to crops and pasture. As well as emitting carbon dioxide (CO_2), CH_4, N_2O and NH_3 to the atmosphere (Webb *et al.* 2012; Chadwick *et al.* 2011), composting may also produce nutrient rich leachate, emphasizing the importance of impermeable bases for such composting facilities (Amon *et al.*, 2022).



Image 27. Windrows of composted manure, Northern Victoria, Australia. Image courtesy of C Gourley.

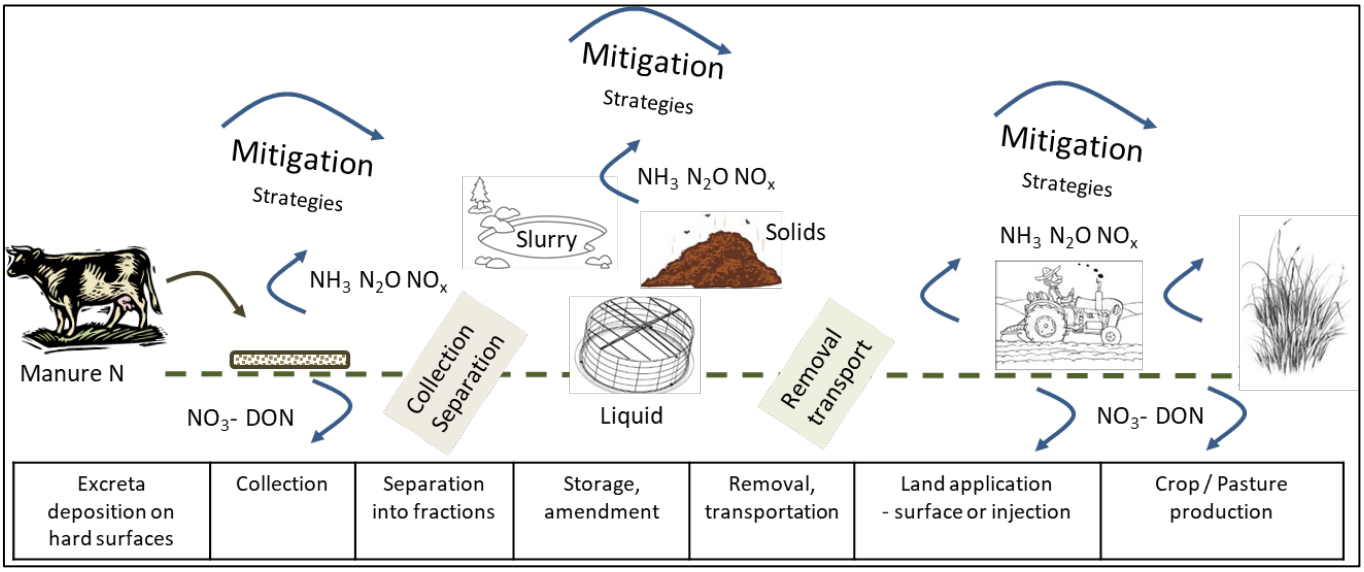


Figure 6.1. Manure management, principal N loss pathways and mitigation targets on a dairy farm, which includes urine, dung and, where used, bedding that is incorporated into manure. (Original graphic produced for this document, © UKCEH 2026.)

6.4 Dung and urine nitrogen available for land application

Quantifying the volumes of manure and urine, and the N excreted by dairy cows, is important for determining manure collection and storage infrastructure, equipment for land application and land area requirements. Dung and urine volumes and excreted N per cow or per herd, for a daily, seasonal or lactation-length timeframe, is generally predicted based on estimates of dairy cow milk production, DM intakes, CP intakes, or combinations of these factors (Nennich *et al.* 2005). However, these estimates are most relevant immediately after excretion and do not reflect the losses of N and mass that occur along the manure management chain (Figure 6.1).

While N excreted in dung and urine from cattle within the dairy farm is not used to determine a whole-farm N balance (see section 4.1), it is central to field N balances. A manure N inventory enables an estimate of the total manure N currently available for land application. Matching this available N supply with estimated N requirements of crops and pasture across the farm (as well as other nutrients provided in manure such as P, K and S) is important in optimizing NUE. The nutrient requirements of crops and pastures on a dairy farm may be totally, partially, or only marginally met by the generated and stored manure, including any urine stored separately. Effective use of manure will reduce fertilizer inputs and increase crop yields, which will offset feed imports and these outcomes will greatly improve the farm N balance.



Image 28. Open slurry storage, NW China. Image courtesy of C Gourley.

The N available in stored manure is generally determined from an assessment of the mass/volume of the storage (i.e., tank, pond or stockpile), manure density, moisture content, and total N and ammoniacal N content. The difference between total N and ammoniacal N is an estimate of the organic N content. These fractions apply to all forms of excreted nitrogen, including urine and dung, and both liquid manure and solid manure (including urine and bedding). The values also change over time as components are mixed, and as chemical processes and losses to the environment occur.

Similar to determining the N content of imported feed, a tiered approach for determining manure N content is recommended.

- Tier 3 data relies on the N content for farm manure sources being considered (including urine, dung, bedding and any other components), based on accurate sampling and chemical analysis.
- Tier 2 data utilises local or national validated information on N content of manure types.
- Tier 1 data relies on more generic estimates of N contents of manure types from guidance documents.

Actual nutrient content of manure sources on any farm can vary widely, so a tier 3 approach, requiring laboratory analysis of farm-specific manure stores, is recommended. The sampling and analysis of manure just prior to field application will assist with refining nutrient application rates. In situ tests can be used if analysis services are too slow or expensive. A series of targeted measurements can also be informative to demonstrate the effectiveness of storage systems in retaining in situ N and other nutrients.

Standardized sampling methodologies (Peters and Combs 2003) should be used when collecting samples of manure for analysis. High sample variability is a common issue, particularly in single or primary pond storages where stratification of liquid manure occurs. Similarly, the moisture and N content can vary substantially through the profile of manure stockpiles.

Monitoring the N:P ratio of stored manure over time may also be used as means of quantifying N losses, as the P content generally remains constant. However, the inherent variability in N content, forms and moisture in manure stores may overshadow meaningful information. Temporal comparisons of fresh and stored manure can help understanding.

Average N content values are generally available for different manure types (for example see Table 6.2). However, more locally sourced information is recommended (tier 2), as it is more likely to reflect the production, manure management and storage systems within a region.



Image 29. Collecting manure samples from an open slurry storage, Northern Victoria, Australia. Image courtesy of C Gourley.

The different types of collected and stored dairy manure (freshly washed or scraped manure, first pond sludge, second pond effluent) will contain varying amounts of organic and inorganic N fractions (Table 6.2). Initially, N forms will depend on the dairy cow diet, collection methodology and frequency, and surface and climate conditions. Sludge from the first pond has a high proportion of organic N forms,

which may potentially mineralize over several years after land application. Sludge will also contain a smaller proportion of ammonium N which is readily available N to crops or pastures.

Second and subsequent pond effluent typically has a low solids content. Depending on the storage time, this effluent will have a higher ammonia-N content (50% to 90% of total N) and comparatively lower organic N content. Therefore, a high proportion of the total-N is readily plant available, with added N supply comparatively short lived. The solid fraction may be used as a P source while the liquid fraction is suitable as an N source because of rapid soil infiltration and lower P loading.

Mechanical separation of solid and liquid fractions, such as screw press separators, result in a solid faction with a higher P to N ratio, and a higher proportion of organic N, and conversely a liquid fraction with a higher proportion of inorganic N.

Solid-liquid "segregation" involves fresh urine and dung collected and stored separately, while solid-liquid "separation" involves the application of mechanical techniques to separate the factions (Amon *et al.* 2022). Where possible, the first of these can significantly reduce energy costs.



Image 30. Surface spreading solid manure, WI, USA. Image courtesy of C Gourley.

Composted solids will also have a higher P to N ratio, with remaining N in largely stable forms, resistant to microbial degradation and poorly plant available in the shorter term.

Table 6.2. Dry matter composition, N forms and concentrations for differing manure types collected from commercial dairy farms (no bedding). (Modified from Chastain and Camberato, 2023.)

Manure Type	Fresh Dung	Manure Scraped from open yards	Fresh Liquid Manure	Manure Slurry	Lagoon Surface Water	Lagoon Sludge	Agitated Lagoon (Liquid & Sludge)
Moisture	86%	67%	96.2%	93%	99.4%	93.9%	97.0%
Total Solids	14%	33%	3.8%	7%	0.6%	6.1%	3.4%
	kg / tonne[1]		kg / 1,000 litre				
NH4 - N	0.85	1.00	0.66	1.13	0.38	0.74	0.56
Organic N [2]	4.14	6.5	0.78	1.63	0.22	1.06	0.64
Total – N	4.99	7.50	1.44	2.76	0.6	1.80	0.83

Fresh Dung refers to collected dung without bedding or water. Manure scaped from open yards will often be drier due to evaporation (depending on climate). Fresh liquid manure from washing manure covered surfaces; Manure Slurry refers to mixed dung and urine; Lagoon Surface Water, refers to the liquid at the top of a slurry lagoon, noting that slurry solids will tend to settle to the bottom as Lagoon Sludge; Agitated Lagoon represents the product of stirring the lagoon.

[1] Wet weight sample analysis; [2] Organic N = Total N - NH_4 -N

Manure N has a lesser plant availability than fertilizer N applications because a significant part is present as organic compounds. Plant available N (PAN) is estimated from the ammonium-N, nitrate-N and organic-N content. The mineral nitrogen fraction, usually determined in the form of ammonium N analysis, is subject to transformation and volatilization losses of NH_3, substantially influenced by the method of land application and incorporation (examples provided in Table 5; Bittman *et al.* 2014).

The organic N forms in land-applied manure need to be mineralized through microbiological processes, with mineralization and immobilization rates influenced by factors such as soil clay content, temperature, moisture content, aeration, microbial communities, pH and other nutrient availability. The supply of PAN from organic N mineralization can continue be effective over several growing seasons, albeit with a declining contribution as the N becomes incorporated into recalcitrant organic matter (Table 6.4).



Image 31. Trickle-hose (also called 'trailing hose') surface application of slurry to pasture, South-eastern Australia. Image courtesy of C Gourley.

Plant available N from land applied manure is calculated as:

$$PAN = NH_4\text{-N retained after application} + \text{organic N-mineralized} \quad [12]$$

where the NH_4 -N retained after application is predicted from the ammoniacal-N content x a discount factor, accounting for the manure type and incorporation method (Table 5, taking account of benefit of reducing ammonia losses), and organic N-mineralized is the organic N content x a mineralization factor, accounting for manure type and years since application (example provided in Table 6.4).

It is important to calculate the required manure application to land, based on the target nutrient application rate (kg/ha). For irrigation systems the volume of effluent applied will be required (i.e. ML or mm applied per ha). For more solid material, this requires the mass or volume of manure applied (i.e., ton or cubic metres/ha). In both cases the mass or volume is multiplied by the nutrient concentrations (volumes need to be adjusted for density). This may also require the regular calibration of manure, urine and compost application equipment.

Table 6.3. Estimated inorganic N availability from differing dairy manure types and application methods. The table shows how estimated nitrogen availability increases with rapid incorporation, injection or band spreading because of the nitrogen saved by reducing ammonia and other emissions. (Modified from Sullivan, 2020.)

	Manure type					
	Storage pond /effluent	Thin slurry	Thick Slurry	Solid manure	Composted manure	Poultry manure
Dry matter content	<1%	1-5%	5-10%	>10%	>40%	>10%
Time until incorporation:						
Immediate incorporation (<1 hr)	0.95	0.95	0.95	0.95	1.00	0.95
Incorporation (< 1 day)	0.95	0.70	0.60	0.50	1.00	0.70
Incorporation Day 2	0.95	0.60	0.45	0.30	1.00	0.50
Incorporation Day 7	0.95	0.55	0.40	0.20	1.00	0.40
Directed application methods:						
Subsurface injection		0.95	0.95			
Surface band (partial incorporation)		0.85	0.70			
Surface band (no incorporation)		0.75	0.60			

Table 6.4. Estimated proportion of organic N available for plant uptake from differing manure types after land application and in subsequent years. (Modified from Sullivan, 2020.)

Manure type	Estimated proportion of organic N mineralized and plant available					
	Dry matter	Year 1*	Year 2	Year 3	Year 4	Years 5 to 9
Storage pond /effluent	< 1%	0.40	0.15	0.07	0.03	0.02/year
Thin slurry	1 - 5%	0.40	0.15	0.07	0.03	0.02/year
Thick slurry	5 - 10%	0.30	0.15	0.07	0.03	0.02/year
Solid scrapped stockpile	> 10%	0.30	0.15	0.07	0.03	0.02/year
Mechanically separated solids	> 20%	0.10	0.05	0.05	0.03	0.02/year
Stabilized compost	> 30%	0.10	0.05	0.05	0.03	0.02/year
Solid poultry manure	> 10%	0.50	0.15	0.07	0.03	0.02/year

*Year 1 = proportion in year of application

Chapter 7: Farm-grown forage nitrogen use efficiency

Key information

- 'Farm-grown' (or 'home-grown') forage refers to feed and forages that are grown on the same farm as where they consumed by livestock.
- Determining NUE for farm-grown feed and forages focuses on N inputs such as mineral fertilizer and manure, N fixation by legumes, organic soil amendments, and wet and dry N deposition, soil N from previous crops, and N outputs in harvested crops and forages.
- System boundaries generally include the paddock / field over a typical crop growth cycle.
- Where: Crop NUE = [Σ (N outputs) / Σ (N inputs)]
- Cropping is generally simpler with inputs and outputs easy to define.
- Grazing pastures or forages, or combinations of cropping and grazing within the same areas, requires estimates of DM and N intakes, N excreta loads by grazing animals.

7.1 Field-scale N inputs

In the absence of additional inputs, crop and forage yields are commonly constrained by a deficiency in plant available reactive N, due to removed N in harvested crops / pasture and other loss pathways. Plant N uptake requires ammonium and/or nitrate N in varying amounts throughout the growing season, and this can be supplied through ongoing mineralisation of organic N forms (from decomposing plant material), biological nitrogen fixation, and or by applications of inorganic and organic fertilizer and manure N inputs.

Nitrogen fertilizer is commonly used in pasture and mixed animal cropping farms to promote plant growth and increase crop yields. Mixed animal cropping farms typically involve the cultivation of a variety of crops alongside the raising of livestock, such as dairy cattle.



Image 32. Inorganic fertilizer N delivery, Southeastern Australia. Image courtesy of C Gourley.

There are many factors identified, both separately or in combination, which can impact on crop and pasture yield response to applied fertilizer and manure N inputs. These include existing soil N availability, environmental factors such as soil moisture and temperature and sunlight including day-length, incidence of pests and diseases and wildlife, previous or current legume content and contribution of biologically fixed N, and the status of other soil nutrients.

High N fluxes at the farm and paddock scales are common to most advanced dairy systems (Gourley *et al.* 2012b; Zhang *et al.* 2017), with inorganic N fertilizer often the dominant N input for both cropping and intensive grazing systems globally. Additionally, there can be high N loads excreted by grazing animal deposited unevenly across the farm landscape (Aarons *et al.* 2017).

7.2 Calculating crop and pasture NUE

Methods used to estimate the efficiency of use of N inputs by crops and pastures vary depending on the specific agronomic question and timeframe to be addressed. For example, the use of the stable isotope ^{15}N enables tracing the movement and transformation of specifically applied N sources to determine their recovery by plants.

Additionally, agronomic N efficiency (also referred to as Apparent N recovery) is used to estimate the uptake of freshly applied N (Norton *et al.* 2015), and is based on the equation:

$$\text{Apparent Crop NUE} = 100 * \text{Crop N uptake (kg ha}^{-1}) / [\text{N applied (kg ha}^{-1}) - \text{N uptake by control crop (kg ha}^{-1})] \quad [13]$$

where the denominator accounts for N applied (e.g., fertilizer, manure) minus N taken up by the crop or pasture (i.e., control crop) with no N additions in that growing season.

However, the most common crop or pasture NUE indicator is a simple input-output mass ratio is appropriate for steady state systems where there are no major changes in N inputs (Norton *et al.* 2015; EU N expert panel 2015), where:

$$\text{Crop NUE} = 100 * \text{Crop N uptake (kg ha}^{-1}) / [\Sigma \text{ N applied (kg ha}^{-1})] \quad [14]$$

Where crop (or pasture) N uptake is determined the harvest or grazed DM removed x N content, and Σ N applied is the sum of all N inputs, including fertilizer N, manure N and BNF, for a given season or growth cycle.

The system boundary for crop or pasture NUE determination is generally at a field or paddock scale, as N removed through harvesting (or through a grazing rotation) may remain within the farm boundary. Ideally crop NUE applies to a standard crop or pasture growing season, where there may be a single or multiple applications of fertilizer or manure N applied. The simple input – output assessment described in equation 13 does not account for any increase or decrease in soil N stock.

Inputs of N from BNF by legumes at the beginning and throughout the growing season are generally based on estimates of the N content of the legume and the annual yield (kg DM/ha), which is also discounted for soil nitrogen supply (See section 4.3). The amount of legume derived N needs also to be adjusted based on the amount of N from legumes that was removed in a previous harvest or left by a previous crop (Norton *et al.* 2015).



Image 33. Cereal grain is a common supplementary feed source for dairy cows in Australia. Image courtesy of C Gourley.

7.3 Nitrogen inputs in grazing dairy systems

For cropping systems, N inputs and outputs at a field scale are commonly reliable, based on farmer records, fertilizer N content and harvested mass or volumes. Commonly, tier 2 data will be required for N concentrations of harvested grains and forages or N inputs in manures.

In contrast, there is usually no direct measure of N inputs in excreta or removal of N by grazing animals. In this case, the mass of N removed by grazing can be ideally estimated from an energy balance (refer to section 5), or using default values based average daily animal intakes, stocking density and/or local knowledge of pasture/forage productivity and N concentrations of grazed pastures/forages. The N inputs through cow excreta can be estimated through the determination of NUE_{Milk} and dairy cow excreted N (equation 5).

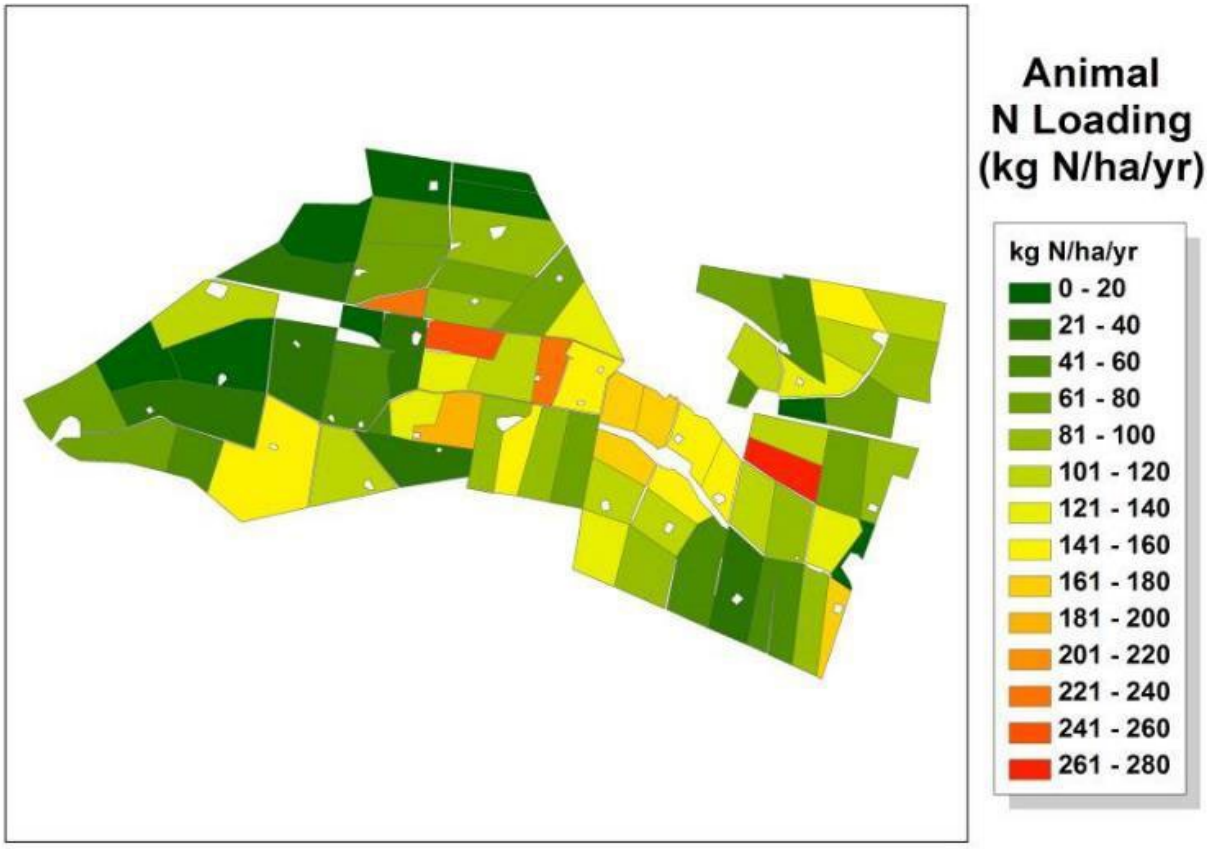


Figure 7.1. An example of annual N inputs from dairy cow excreta to different grazed fields. The high degree of spatial variability of N inputs reflects the contrast between intensively and extensively grazed fields. (Reproduced from Aarons *et al.*, 2017.)

There may also be combinations of grazing and harvesting undertaken within the same field, as may be the case where pastures are grazed, then further forage growth is conserved for a silage or hay harvest, or harvested first and then grazed in short growing seasons. An annualized assessment based on the sum of all N inputs, including fertilizer and collected-manure applied, and manure directly applied by grazing animals, and N removal, including pasture/forage removed by grazing animals and harvesting may be required.

7.4 Interpreting crop and pasture NUE

The simplest interpretation of crop or pasture NUE is whether N is in net deficit, with N being depleted from the field (i.e., NUE > 1) or whether N is in net surplus (NUE <1), where reactive N is likely to be lost from the field to the broader environment.

However, any interpretation of crop or pasture NUE should consider the system context. Dairy production systems and mixed cropping – animal systems are recognized as inherently N-leaky, because of multiple N transformations, the low conversion of feed N into milk N, and the N-rich and highly volatile N forms in excreted N.

The conceptual framework outlined for whole-farm NUE (Section 4.5, this volume) is equally applicable in assisting in the interpretation of crop and pasture NUE assessment. Further information can be found in the specific INMS Guidance Document on Nitrogen Use Efficiency (Lassaletta & Sanz Cobeña, 2026).

Chapter 8: Nitrogen budgets as a combined framework for reporting N use efficiency indicators

The diversity and complexity of N management practices on a dairy farm and the associated pathways and transformations of N fluxes, highlight the need for a suite of whole-farm, as well as within-farm NUE indicators, specific to dairy production system typologies.

Whole-farm and component N budgets can provide useful performance indicators, which can be internationally comparable. Whole-farm indicators, including NUE, N surplus and Milk production N surplus, can be used to focus industry efforts on increasing N use efficiency and reducing N emissions from dairy farms. Within-farm N efficiency indicators, including milk NUE, manure collection and reuse and crop/pasture NUE will assist farmers and advisors to target specific improvements in N management and N loss mitigation options. Quantifying these N fluxes and efficiencies is therefore an important part of identifying where improvements in N use and recycling of within-farm N pools can be made.

Consequently, to determine appropriate farm nitrogen indicators, the following information is required:

1. A detailed description of the dairy farm system, including categorizing the farm system within a global dairy farm typology,
2. Quantification of the dairy farm productivity area, including defined land-uses, confinement areas and housing infrastructure,
3. Identification and quantification of all farm N sources and N contents for N input and N export determination, including, but not limited to, fertilizer, feed, manure, biological N fixation, atmospheric deposition, milk and animals,
4. Proportional reliance on home-grown and feed imported from outside the farm,
5. Cow or herd level N intakes, milk production and milk N analysis,
6. Estimates of manure N excreted, locations and proportion of time cows spend in various locations, and associated manure collection practices,
7. Manure and fertilizer N application strategies and crop and forage yields.

The nitrogen indicators and reporting frameworks should be developed along with farmers and industry advisors to meet the dual goals of production and environmental performance, utilise readily available farm-based information and enable benchmarking and guidance for improvement. This applies whichever indicator focus of communication is chosen, for example NUE or nitrogen surplus, or full visualization of the farm nitrogen budget. As 'optimum' NUE values are context and farm system specific, solely comparing NUE indicators between farms/regions/countries can be problematic. It is also important to assess these indicators over time to ensure ongoing performance improvements are being achieved.

Improved N management for dairy farms requires tailored solutions to common systematic challenges and specific dairy production typologies. Examples include energy deficits and low milk yields per cow in low-input and traditional dairy systems, excess N intakes and over-fertilization in specialised production systems, and poor manure collection, storage and land-spreading techniques across all dairy production typologies.

Chapter 9: Nitrogen budgets for international dairy farm systems

This section describes dairy farm nitrogen budgets for seven contrasting international dairy system typologies, defined as follows, and illustrated by one or two case studies for each type (Section 2.1.1, this volume).

Type 1: Small-scale, low input dairy farms (typically <6 cows), with low quality feed and daily milk production, and often grazing and forage collection from common lands – Represented by dairy systems in South Asia

Type 2: Medium-scale family run dairy farms (typically 40 – 120 cows), with seasonal grazing and confined housing, including farm-grown forage crops – Represented by dairy systems in western Europe and UK

Type 3: Intensive grazing systems (typically 250 and 600 cows), with managed pastures on private land and limited or no housing – Represented by dairy systems in New Zealand and Australia. This type is divided into two subtypes: a, with little or no purchased supplementary feeding, and b, with purchased supplementary feeding.

Type 4: Medium intensive, confined cows with mixed cropping (typically 150-300 cows) - Represented by dairy systems in Canada.

Type 5: High intensity housed livestock, mixed-farm systems, with animals confined all year in free stalls, high levels of mechanization, balanced rations, large herds (typically 250 - 1000 cows), manure management infrastructure and associated crop production – Represented by dairy systems in USA.

Type 6: Landless housing systems (typically 250 - 600 cows), with cows in confinement housing and concentrates and forage crops are purchased or produced externally – Represented by dairy systems in China.

Type 7: Collective farm systems with centralised feed and manure management (typically 6 – 10 farms totalling >2000 cows) – Represented by dairy systems in Japan.

Seasonal and annual information was used to generate the case-study N budgets, including the number of lactating cows, milk production per cow and/or herd, feed types, rations fed, farm infrastructure, locations cows visited, and time spent, and manure collection and storage practices.

Data utilized for the dairy system typologies ranged from detailed farm records including specific laboratory determined N contents of feed and milk (Tier 3 data), to the use of industry average farm information (Tier 1 data). Commonly, N budgets for each of the case-studies includes a mix of factual farm data, relating to cow numbers, farm size, feed types and diets (Tier 3 data) and representative regional N contents for feed and milk, atmospheric deposition, N fixation, and estimates of cow time in specific locations on a seasonal basis (Tier 2). Sources of data used to determine N budgets are identified for each dairy system typology provided. The provided case studies include:

- System descriptions and N management practices
- Flow diagrams of nitrogen inputs, outputs and transformations
- Whole farm N budgets: NUE, N surplus and milk N surplus
- Animal Feed and milk NUE
- Fertilizer N use
- Manure N generation
- Manure N collection and storage.

9.1 International dairy typology 1: Small-scale, low-input dairy farms





Image 35. Feeding collected green forage Nepal. Both images courtesy of K Dahal.

Image 34. Nepalese common-land grazing.

Table 9.1. General characteristics of international dairy typology 1.

Small-scale, low-input dairy farms	
Typical farm system	Small-scale and low input subsistence dairy production. A single household usually manages a small number of animals including one or two cows, with the produced milk providing subsistence food and livelihood.
Countries / regions generally applicable	South Asia: Nepal, India, Pakistan, Sri Lanka. The cow is sacred for Hindus, having social, cultural, economic and religious significance. Agriculture remains the main occupation in South Asia, with livestock accounting for ~26% of agricultural GDP. India has the largest cattle population and milk production, globally.
Typical primary feed sources and quality	Crop residues, rice, wheat straw, maize stovers, tree fodder, leaf litter and other green fodder collected from cultivated lands and forest are the major feeding resources. Feed is often of poor quality, with straw making up most of the diet during winter and summer; some supplementation with grain and byproducts.
Typical dairy cows	There are seven indigenous cattle breeds in South Asia: Lulu, Achhami, Siri, Khaila, Pahadi, Yak/Nak and Terai. The most common are Pahadi and Tarai, with typical mature body weight 125-298 kg and milk yields ~1-4 l/day/cow (lactation 9-10 months). Exotic breeds such as Friesian and Jersey are also present in more intensive systems.
Typical housing and confinement	Cows graze outside for 4-6 hours depending upon locality and season; remaining time is spent in small tie-stall barn or yard. For ~ 3 months over winter, animals are penned during the day in fallow cropping land (15-20 days per field), moved to barns at night.
Typical manure management	Around 50% of excreted manure is directly excreted in pasture of cropping land and 50% is deposited in a small tie-stall barn or yard. Collected manure is commonly composted and uncovered during the summer-rainy season and low quality manure is surface applied for field crops. The use of dung for cooking is common. In some places, mostly in warm regions manure used for biogas production is becoming popular.
Typical crop and pasture management	Small-scale and low input crops include rice, maize, wheat and millet, with crop residues a major source of feed for livestock.
Common opportunities to improve NUE	Very low milk production per animal due to poor quality of feed and animal health. Manure management practices exacerbate N losses.



Image 36. Nepal. Manure reuse for crops. Image courtesy of K Dahal.

Table 9.2. Details of Nepalese dairy farm used as case study.

Farm characteristics	
Herd size	4 lactating cows
Average cow weight	200 kg
Lactation length	280 days
Farm area	2 ha
Stocking rate (cows/ha)	2.0 cows/ha
Cow milk production per year	924 L
Milk from imported feed:	490 L
Milk from home grown feed	434 L
Proportion of feed imported	53%

Data sources

- Industry average milk production and feed intakes for low-input traditional dairy production in Nepal (Tier 1 data).
- Descriptions of typical herd / cow management (Tier 2 data).
- International feed and milk N concentration estimates, BNF and atmospheric deposition estimates (Tier 1 data).
- See: Bhatta BR *et al.* (2018); MoALD (2022); Upreti CR *et al.* (2020).

Whole-farm nitrogen budget:

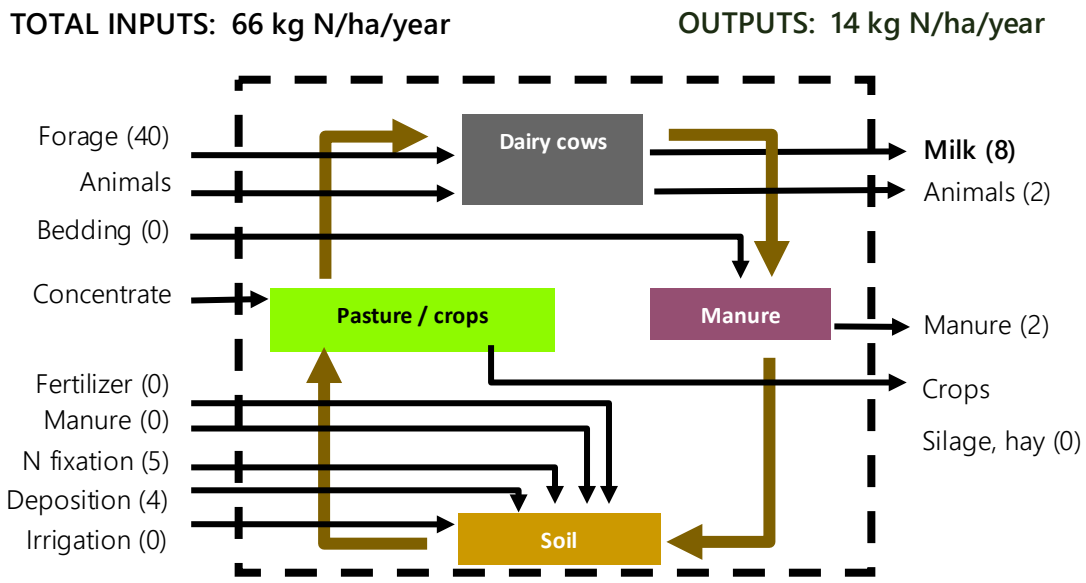


Figure 9.1. Whole-farm nitrogen budget for South Asian small-scale, low-input dairy farming, as an illustration of Type 1. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Table 9.3. Indicators for the farm nitrogen budget, together with indicators related to intake, milk and excretion for South Asian small-scale, low-input dairy farming, as an illustration of Type 1.

Whole-farm nitrogen budget indicators		
Nitrogen Use Efficiency	**N Surplus**	**Milk Production N Surplus**
15.6%	**52 kg N/ha/year**	**15.5 g N/l**

Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (Dry Matter)				**Milk Production**		
Feed type	**kg/cow/day**	**N%**	**g N/cow/day**			
Pasture/ green fodder	4	2.24	79	Herd	13	L/herd/day
Rice/maize flour	2	1.92	38	Cow	3.3	L/cow/day
Maize stover	3	1.60	48			
Straw	2	1.36	27	Milk N concentration	0.49	N%
Hay	2	1.86	37	Milk N exported	16.1	g N/cow/day
Total			**229**			
Milk NUE	**7.0%**			**Manure N Produced**		
				Cow per day	213	g/cow/day
				Cow per year	78	kg/cow/year
				Herd per year	0.31	tonne/herd/year

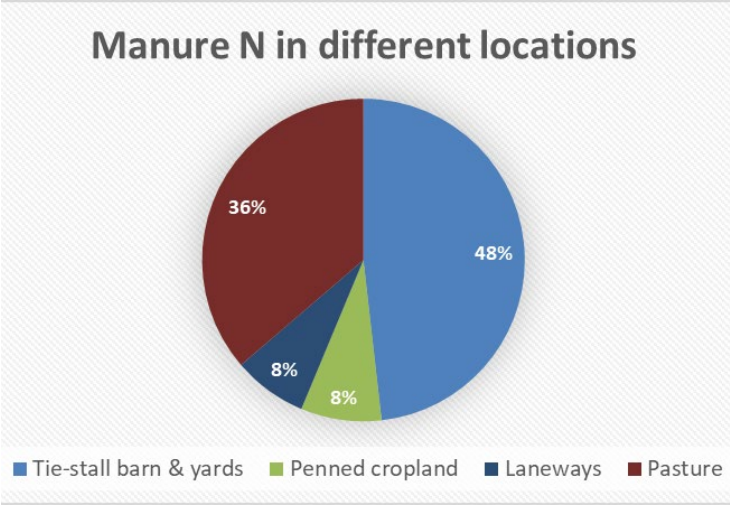


Figure 9.2. Share of manure (including dung and urine) that is excreted in different locations of a South Asian small-scale, low-input dairy farm (Type 1). (Original graphic produced for this document, © UKCEH, 2026.)

9.2 International dairy typology 2: Medium-scale family-run dairy farms



Image 37. Dutch cow housing. Image courtesy of K Groenestein.



Image 38. Dutch cow grazing. Image courtesy of K Groenestein.

Table 9.4. Characteristics of international dairy typology 2.

Medium-scale family run dairy farms	
Typical farm system	Medium-scale family run dairy farms (<100 cows), with seasonal grazing and confined housing, including farm-grown forage crops – In 2018, farms had on average 95 dairy cows and 64 ha of land (80% grassland and 20% forage maize).
Countries / regions generally applicable	Representative of dairy systems in Netherlands, France, Denmark.
Typical primary feed sources and quality	Managed rotationally grazed pastures with an additional one-third of feed (concentrates) imported from other countries. Seasonal growth pattern requires forage conservation and use of purchased supplements. The cows are fed with silage (TMR of maize and grass silage) in confined barns during the evening and night.
Typical housing and confinement	Intensive grazing of improved pastures, with limited grazing (only access to the paddock during daytime in spring-summer). Cattle can be housed permanently or provided with grazing hours during the day.
Typical manure management	Manure deposited depending on grazing time (av. 9000 hours/year), 10-15% deposited on pasture and 85-90% inside barn. More than 90% of dairy farms have conventional housing systems with manure storage under floor storage, ~10% of farms also equipped with ammonia emission-reduction systems (NEMA 2022). Slurry must be stored in leakproof and covered manure storages and must be applied to land using low-emission techniques during summer (February to August). Outside storage only when inside manure pit is full.
Typical crop and pasture management	Increasing reliance on crop production as grazing time on pasture decreases due to increasing environmental regulations which aim to reduce N losses.
Typical crop and pasture fertilization	Manure N application limits ranged from 170 to 250 kg ha^{-1} yr^{-1}, depending on farm-specific permits.

Common opportunities to improve NUE	Decreasing protein intake and applying innovative and low-emission housing systems.
Other comments	Declining number of smaller family farms, due to increasing specialization, robotic milking systems and environmental requirements.



Image 39. Dutch robotic milking. Image courtesy of K Groenestein.

Table 9.5. Details of Dutch dairy farm used as case study.

Case study farm characteristics Dutch family managed dairy farm	
Herd size	112 lactating cows
Average cow weight	550 kg
Milking area	55 ha
Stocking rate (cows/ha)	2.04 cows/ha
Cow milk production per year	9457 L
Milk from imported feed:	350,090 L
Milk from home grown feed	709,094 L
Home forage consumed	11,400 kg DM/ha
Purchased feed to total feed ratio	33%

Data sources:

- Factual survey data from a typical Dutch dairy farm, including milk production, feed intakes and N content, animals and fertilizer inputs (Tier 3 data).
- Cow locations and time allocated, Biological N fixation and atmospheric deposition estimates from national studies (Tier 2).
- See: Bruggen, C van *et al.* (2022); Oenema J, Oenema O (2022).

Whole-farm nitrogen budget:

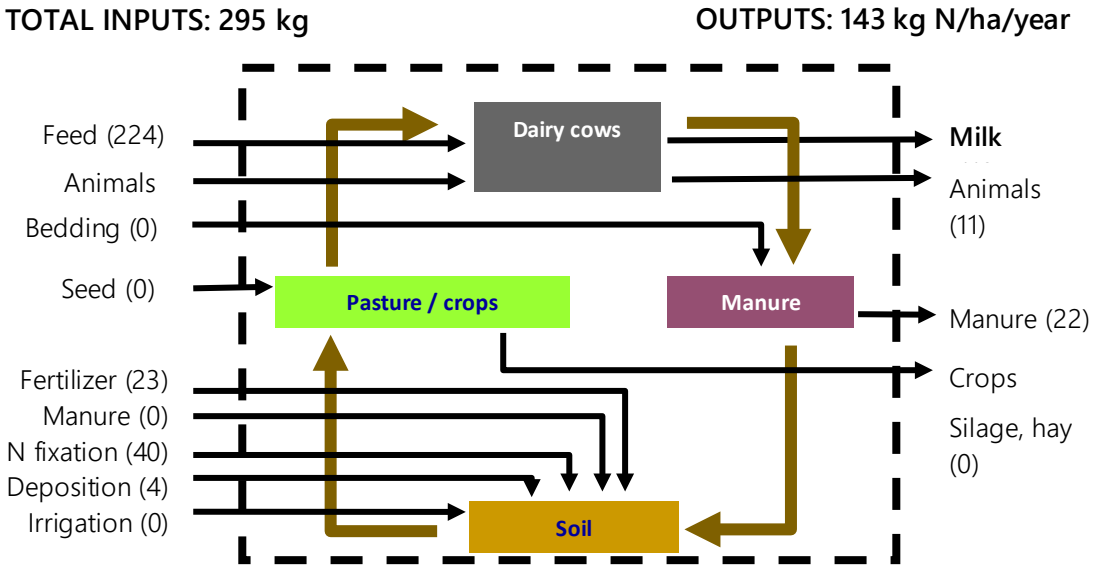


Figure 9.3. Whole-farm nitrogen budget for Dutch medium-scale dairy farm, as an illustration of Type 2. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Table 9.6. Indicators for the farm nitrogen budget, together with indicators related to intake, milk and excretion for Dutch medium-scale dairy farm, as an illustration of Type 2.

Whole-farm nitrogen budget indicators		
Nitrogen Use Efficiency	**N Surplus**	**Milk Production N Surplus**
44.0%	**153 kg N/ha/year**	**7.9 g N/l**

Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Fresh grass	2	3.7		Herd	2902	L/herd/day
Grass silage	9	2.8		Cow	25.9	L/cow/day
Maize silage	9	1.2				
By-products	4	1.0		Milk N concentration	0.60	N%
Concentrate	3	2.4		Milk N exported	158	g N/cow/day
Total			526			
Milk - NUE	**30.0%**			**Manure N Produced**		
				Cow per day	368	g/cow/day
				Cow per year	134	kg/cow/year
				Herd per year	15	tonne/herd/year

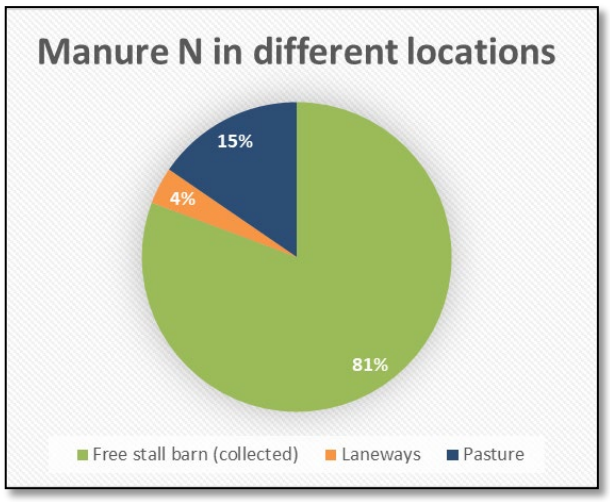


Figure 9.4. Share of manure (including dung and urine) that is excreted in different locations of a Dutch medium-scale dairy farm (Type 2). (Original graphic produced for this document, © UKCEH, 2026.)

9.3 International dairy typology 3a: Intensive grazing systems, with low supplementary feeding



Image 40. New Zealand grazing system. Image courtesy of C Gourley.



Image 41. New Zealand milking yards. Image courtesy of C Gourley.

Table 9.7. Characteristics of international dairy typology 3a.

Intensive grazing with low supplementation	
Typical farm system characteristics	Intensive grazing (generally between 250 and 600 cows), highly managed pastures, on private land. Lactation length can vary with pasture yields. Additional supplementation with use of concentrates or byproducts, usually < 10% of total DM consumed.
Countries / regions generally applicable	New Zealand, less commonly found in United Kingdom, Ireland, United States
Typical primary feed sources and quality	Managed rotationally grazed pastures of varying quality due to species present and seasonal conditions. Seasonal growth pattern requires some forage conservation and use of purchased supplements.
Typical housing and confinement	No permanent housing. Intensive grazing of improved pastures and forage crops. May include designated feeding areas for conserved / purchased feeds, and where manure is collected.
Typical manure management	The majority of manure is deposited and recycled on grazed pastures. <10% manure collection, mainly in holding areas, milking parlour, designated feeding areas. Wash systems with effluent storage in open ponds before land irrigation.
Typical crop and pasture management	Predominately permanent or short-lived grass-based pastures, some clover legumes. Some forage crops. Mismatch between forage growth and animal feed demand requires conservation practices and designated feeding areas.
Typical crop and pasture fertilization	Pastures and fodder crops strategically fertilized to enhance production for grazing or forage conservation; commonly N fertilizer applied following grazing rotations.

Common opportunities to improve NUE	Cows commonly in energy deficit; Excess protein intakes; Poor pasture utilization; Timing and rates of fertilizer N applications may not match pasture uptake.
Other comments	The number of smaller grazing operations with < 200 lactating cows are declining, being replaced with more intensive larger herds with increased reliance on imported feed and fertilizer. In recent years, environmental pressures have seen an increased focused on cow efficiency with total cow numbers trending down while total milk production continuing to increase.



Image 42. New Zealand grazed pasture. Image courtesy of C de Klein.

Table 9.8. Details of New Zealand dairy farm used as case study.

New Zealand: Cool climate, medium rainfall, flatland dairy farming on well-drained soil	
Herd size	424 lactating cows
Average cow weight	405 kg
Average lactation length	266 days
Milking area	160 ha
Stocking rate (cows/ha)	2.7 cows/ha
Cow milk production per year	7280 L
Milk from imported feed:	1,686,672 L
Milk from home grown feed	1,399,938 L
Home forage consumed	11,688 kg DM/ha
Purchased feed to total feed ratio	17%

Data sources:

- Factual survey data of North Island New Zealand dairy farm, including milk production, feed intakes and N content, animal imports and exports and fertilizer inputs (Tier 3 data).
- Cow locations and time allocated; Biological N fixation and atmospheric deposition estimates from national studies (Tier 2).
- See: Monaghan R, *et al.* (2021).

Whole-farm nitrogen budget:

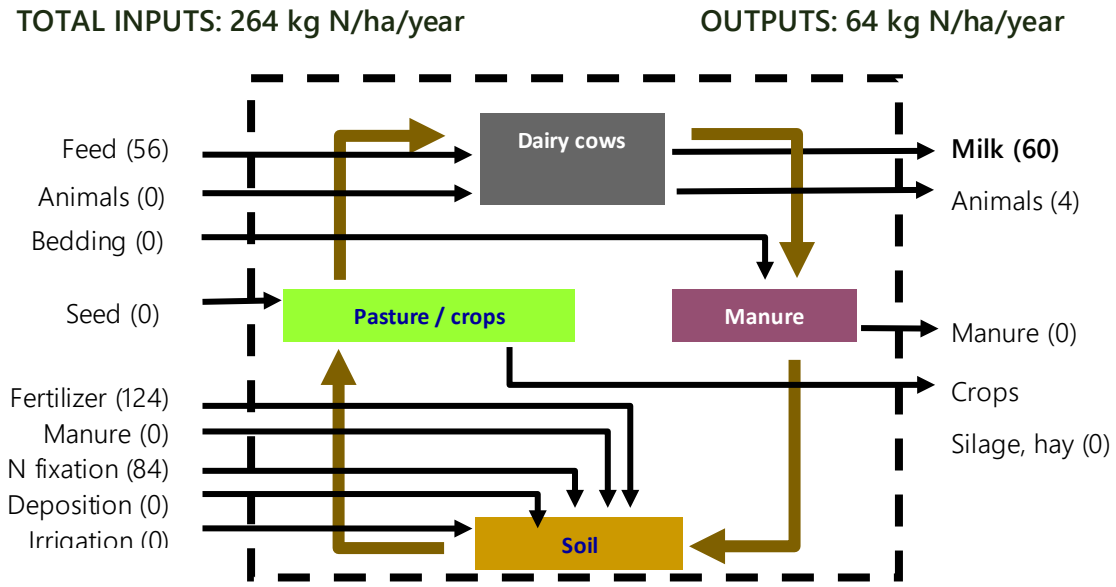


Figure 9.5. Whole-farm nitrogen budget for New Zealand grazing-based dairy farm, as an illustration of Type 3a. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Table 9.9. Indicators for farm nitrogen budget, together with indicators related to intake, milk and excretion for New Zealand grazing dairy farming, as an illustration of Type 3a.

Whole-farm nitrogen budget indicators						
Nitrogen Use Efficiency		**N Surplus**		**Milk Production N Surplus**		
24.0%		**200 kg N/ha/year**		**10.2 g N/l**		
Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Pasture	12.8	3.49		Herd	4635	L/herd/day
Turnips	0.2	3.20		Cow	11.3	L/cow/day
Palm Kernal	1.6	2.72				
Maize silage	0.4	1.14		Milk N concentration	0.76	N%
Pasture silage	0.3	1.60		Milk N exported	86	g N/cow/day
Fodder beet	1.2	1.6				
Total			505	Manure N Produced		
Milk - NUE	16.0%			Cow per day	424	g/cow/day
				Cow per year	155	kg/cow/year
				Herd per year	64	tonne/herd/year

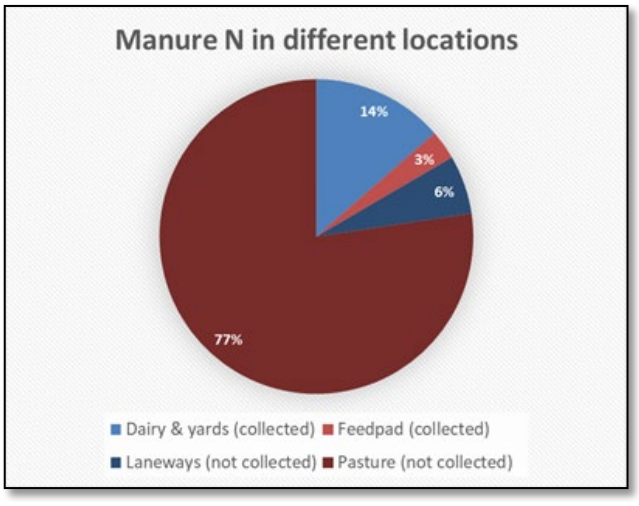


Figure 9.6. Share of manure (including dung and urine) that is excreted in different locations on an New Zealand intensive grazing dairy farm (Type 3a). (Original graphic produced for this document, © UKCEH, 2026.)

9.4 International dairy typology 3b: Intensive grazing systems, with purchased supplementary feeding.



Image 43. Australian grazing system.
Image courtesy of C Gourley.



Image 44. Australian rotary dairy.
Image courtesy of C Gourley.

Table 9.10. Characteristics of international dairy typology 3b.

Intensive grazing system with purchased supplementary feeding	
Typical farm system characteristics	Year-round intensive grazing (generally between 250 and 600 cows), highly managed pastures, on private land. Pasture intake is generally supplemented with additional grain or concentrates, usually 20-40% of total DM consumed, through bale feeding or in designated feeding areas.
Countries / regions generally applicable	Australia, South America, less common in United Kingdom, Ireland, United States
Typical primary feed sources and quality	Managed rotationally grazed pastures of varying quality due to species present and seasonal conditions. Seasonal growth pattern requires some forage conservation and use of purchased supplements.
Typical housing and confinement	No permanent housing. Intensive grazing of improved pastures and forage crops. May include designated feeding areas for conserved / purchased forages, and manure is collected.
Typical manure management	The majority of manure is deposited and recycled on grazed pastures. <10% manure collection, mainly in holding areas, milking parlour, designated feeding areas. Wash systems with effluent storage in open ponds before land irrigation.
Typical crop and pasture management	Predominately permanent or short-lived grass-based pastures, some clover legumes. Some forage crops. Mismatch between forage growth and animal feed demand requires conservation practices and designated feeding areas.
Typical crop and pasture fertilization	Pastures and fodder crops strategically fertilized to enhance production for grazing or forage conservation; commonly N fertilizer applied following grazing rotations.
Common opportunities to improve NUE	Cows commonly in energy deficit; Excess protein intakes; Poor pasture utilization; Timing and rates of fertilizer N applications may not match pasture uptake.

Other comments	The number of smaller grazing operations with >200 lactating cows are declining, being replaced with more intensive larger herds with increased reliance on imported feed and fertilizer.



Image 45. Australia, manure spreading. Image courtesy of C Gourley.

Table 9.11. Details of Australian dairy farm used as case study.

Southeastern Australia: Cool climate, medium rainfall, undulating pastures	
Herd size	602 lactating cows
Average cow weight	550 kg
Average lactation length	266 days
Milking area	376 ha
Stocking rate (cows/ha)	1.6 cows/ha
Cow milk production per year	8222 L
Milk from imported feed:	1,049,961 L
Milk from home grown feed	3,899,921 L
Home forage consumed	8,524 kg DM/ha
Purchased feed to total feed ratio	21%

Data sources:

- Factual survey data of South-east Australian dairy farm, including milk production, feed intakes and N content, animals and fertilizer inputs (Tier 3 data).
- Biological N fixation and atmospheric deposition estimates from national studies (Tier 2).
- See: Aarons SR *et al.* (2020); Gourley CJP *et al.* (2012a).

Whole-farm nitrogen balance:

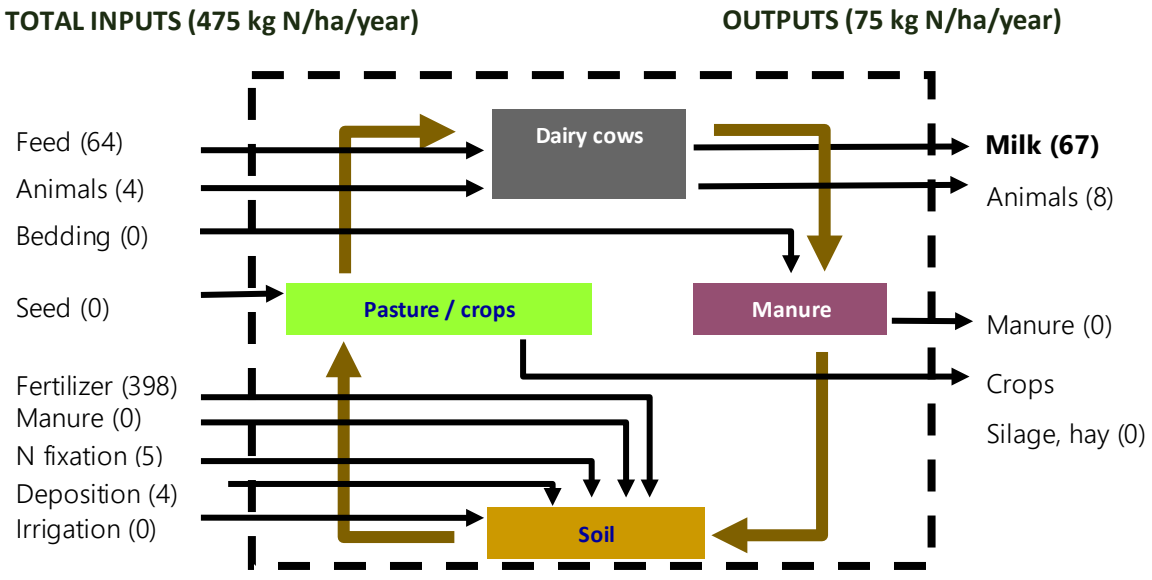


Figure 9.7. Whole-farm nitrogen budget for Australian grazing with supplementation dairy farm, as an illustration of Type 3b. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Table 9.12. Indicators for farm nitrogen budget, together with indicators related to intake, milk and excretion for Australian intensive grazing with purchased supplementary feed dairy farm, as an illustration of Type 3b.

Whole-farm nitrogen budget indicators						
Nitrogen Use Efficiency		**N Surplus**		**Milk Production N Surplus**		
15.8%		**400 kg N/ha/year**		**30.4 g N/l**		
Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Pasture	11	3.2	347	Herd	13,630	L/herd/day
Grain	4	2.2	94	Cow	25.0	L/cow/day
Pellets	4	2.6	99			
Silage	3	2.3	75	Milk N concentration	0.51	N%
Hay	2	1.7	35	Milk N exported	128	g N/cow/day
Total			650	Manure N Produced		
Milk - NUE	19.7%			Cow per day	522	g/cow/day
				Cow per year	191	kg/cow/year
				Herd per year	104	tonne/herd/year

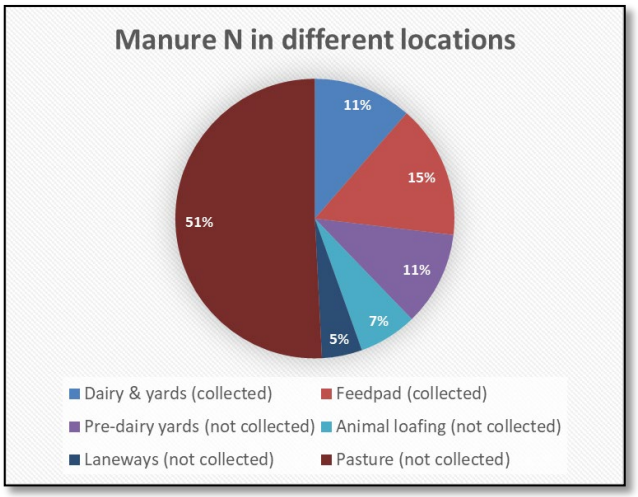


Figure 9.8. Share of manure (including dung and urine) that is excreted in different locations of an Australian intensive grazing with purchased supplementary feed dairy farm (Type 3b). (Original graphic produced for this document, © UKCEH, 2026.)

9.5 International dairy typology 4: Medium intensive confined cows with mixed cropping



Image 46. Free stall dairy barn in British Columbia, Canada. Image courtesy of S Bittman.



Image 47. Canada Spring growth or Italian ryegrass inter seeded in juvenile corn. Image courtesy of S Bittman.

Table 9.13. Characteristics of international dairy typology 4.

Medium intensive – Confinement – Mixed cropping	
Typical farm system characteristics	Mixed cropping – fully housed dairy system. Confined free-stall housing of moderate herd size (200 – 300 lactating cows). Generally, family owned and operated with some external labour. Intensive and mechanized feeding systems with high milk production per cow.
Countries / regions generally applicable	Canada, Midwestern United States
Typical primary feed sources and quality	Mixture of grassland for forage harvesting, corn silage and forage (alfalfa), with annual cropping rotation. Seasonal growth requires forage conservation. High dependence on purchased feed such as alfalfa, and high crude protein supplements.
Typical housing and confinement	Permanent housing. Free-stall barns with straw, wood chip or sand bedding and gutter collection systems for manure. Connectivity of milking parlour with barns facilitates manure collection.
Typical manure management	Manure is deposited onto concrete surface, with scraper and washing systems. Liquid manure storage tanks below or above ground and occasionally lagoon systems with 6 month storage capacity, forming surface crusts. Liquid dairy manure land applied to grassland and corn by broadcasting.
Typical crop and pasture management	Grassland and corn for forage harvesting requires conservation practices and large amounts of feed storage, usually in silage bunkers.
Typical crop and pasture fertilization	Grassland and maize silage crops strategically fertilized to enhance production with ~70% slurry manure, 30% fertilizer N.

Common opportunities to improve NUE	Total N inputs applied are likely to be above crop needs. Net N surplus in generated manure. N losses by volatilization at all stages of manure train and leaching from fields. Potential for reducing excess protein dietary intakes, low emission manure spreading and, relay cropping corn (see photo) and manure storage covers.



Image 48. Canadian free stall barn. Image courtesy of S Bittman.

Table 9.14. Details of Canadian dairy farm used as case study.

Mixed cropping dairy system with full confinement	
Herd size	250 lactating cows
Average cow weight	550 kg
Milking area	114 ha
Stocking rate (cows/ha)	2.2 cows/ha
Cow milk production per year	12,556 L
Milk from imported feed:	1,475,330 L
Milk from home grown feed	1,663,670 L
Home forage consumed	16,132 kg DM/ha
Purchased feed to total feed ratio	47%
Proportion manure land applied	92%

Data sources:

- Factual survey data of Canadian dairy farm, including milk production, feed intakes and N content, and fertilizer inputs (Tier 3 data).
- Biological N fixation and atmospheric deposition estimates from national studies (Tier 2).
- See: Sheppard S *et al.* (2011); Thivierge MN, *et al.* (2017).

Whole-farm nitrogen budget:

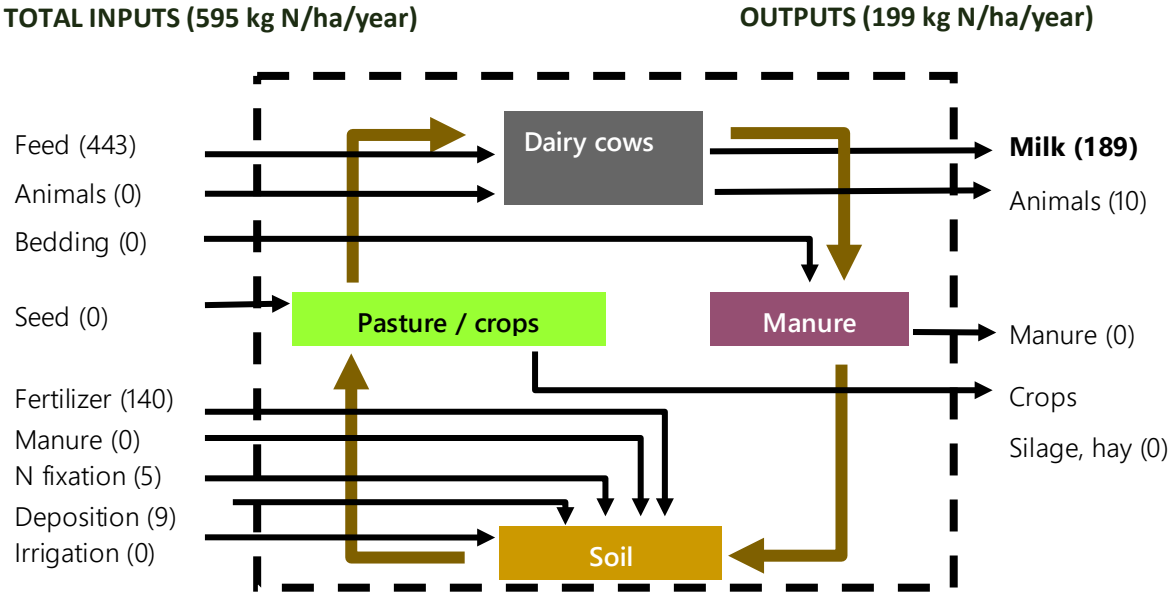


Figure 9.9. Whole-farm nitrogen budget for Canadian confinement system with cropping dairy farm, as an illustration of Type 4. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Table 9.15. Indicators for farm nitrogen budget, together with indicators related to intake, milk and excretion for Canadian confinement system with cropping dairy farm, as an illustration of Type 4.

Whole-farm nitrogen budget indicators						
Nitrogen Use Efficiency		**N Surplus**		**Milk Production N Surplus**		
33.6%		**396 kg N/ha/year**		**14.3 g N/l**		
Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Grass silage/hay	11	2.92	321	Herd	8600	L/herd/day
Corn silage	4	1.4	56	Cow	34.4	L/cow/day
Alfalfa hay	4	3.2	128			
Ryegrass straw	3	0.8	72	Milk N concentration	0.51	N%
Concentrate	2	3.15	63	Milk N exported	175	g N/cow/day
Total			640			
Milk – NUE	**27.4%**			**Manure N Produced**		
				Cow per day	460	g/cow/day
				Cow per year	168	kg/cow/year
				Herd per year	42	tonne/herd/year

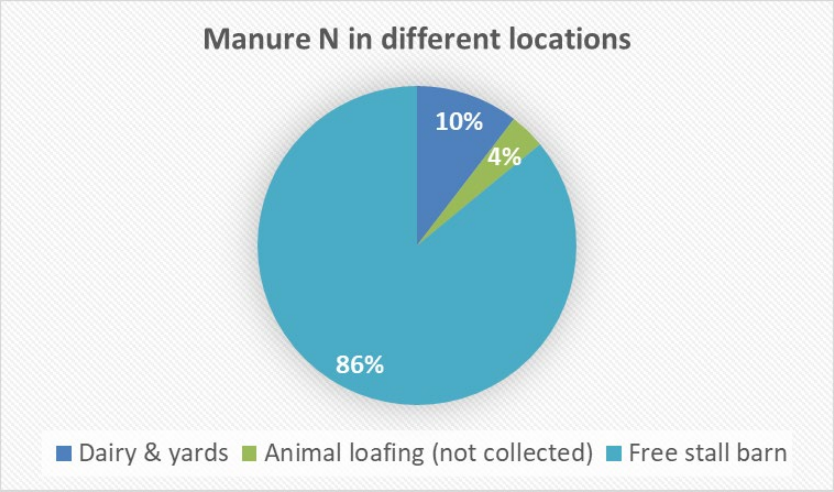


Figure 9.10. Share of manure (including dung and urine) that is excreted in different locations of a Canadian, cropping and housed dairy farm (Type 4). (Original graphic produced for this document, © UKCEH, 2026.)

9.6 International dairy typology 5: High intensity, housed livestock, mixed farming systems



Image 49. Wisconsin, USA, free stall barn. Image courtesy of C Gourley.



Image 50. Wisconsin, USA, harvesting maize for silage. Image courtesy of C Gourley.

Table 9.16. Characteristics of international dairy typology 5.

High intensity, housed livestock, mixed farming systems	
Typical farm system characteristics	High intensity, fully confined free stall barn, total mixed rations, herd size (200 – 1000 cows), associated crop production and manure management infrastructure.
Countries / regions generally applicable	USA, but increasingly common internationally.
Typical primary feed sources and quality	Cows and replacement heifers are fed primarily on farm-grown forage comprising maize silage, alfalfa and soybean. Additional supplementary feed is often purchased to balance the energy and crude protein content of the TMR.
Typical housing and confinement	Typical in the Midwest and Northeast regions of the USA, with standard confinement system (cows in free-stall barns) and rotational cropping.
Typical manure management	Most manure is collected, stored and applied to fields, primarily prior to maize planting during spring and after harvest during fall and winter. Some farms may also have external yards with limited manure collection and management.
Typical crop and pasture management	A typical dairy farm manages approximately 200 - 300 kg total N (fertilizer N, biologically fixed N, manure N and minor N sources) per ha, principally applied to maize crops.
Typical crop and pasture fertilization	Nitrogen input to crops is generally sourced from a combination of N fertilizer (~20%), biologically fixed-N by alfalfa and soybeans (~25%), and manure N sources (~55%).
Common opportunities to improve NUE	Reduced crude protein intake to reduce excretions of urinary urea and subsequent emissions of ammonia and nitrous oxide. Improved storage and land application rates and methods of manure N.
Other comments	High intensity, fully confined free stall barn, total mixed rations, herd size (200-1000 cows), associated crop production and manure management infrastructure.

Table 9.17. Details of USA dairy farm used as case study.



Image 51. Wisconsin, USA, free stall barn. Image courtesy of C Gourley.

United States: Full confinement in free-stall barn Cropping: 70% maize, 26% alfalfa, 4% fallow	
Herd size	241 lactating cows
Average cow weight	600 kg
Stocking rate (cows/ha)	0.7 cows/ha
Cropping area	344 ha
Cow milk production per year	10,280 L
Milk from imported feed:	743,244 L
Milk from home grown feed	1,734,236 L
Home forage consumed	16,132 kg DM/ha
Purchased feed to total feed ratio	30%
Proportion manure land applied	100% to maize crops

Data sources:

- Factual survey data of Wisconsin dairy farm, including milk production, feed intakes and N content, animals and fertilizer inputs (Tier 3 data).
- Biological N fixation and atmospheric deposition estimates from national studies (Tier 2).
- See: Powell JM, *et al.* (2017); Spears RA, *et al.* (2003); Gourley CJP, *et al.* (2012).

Whole-farm nitrogen budget:

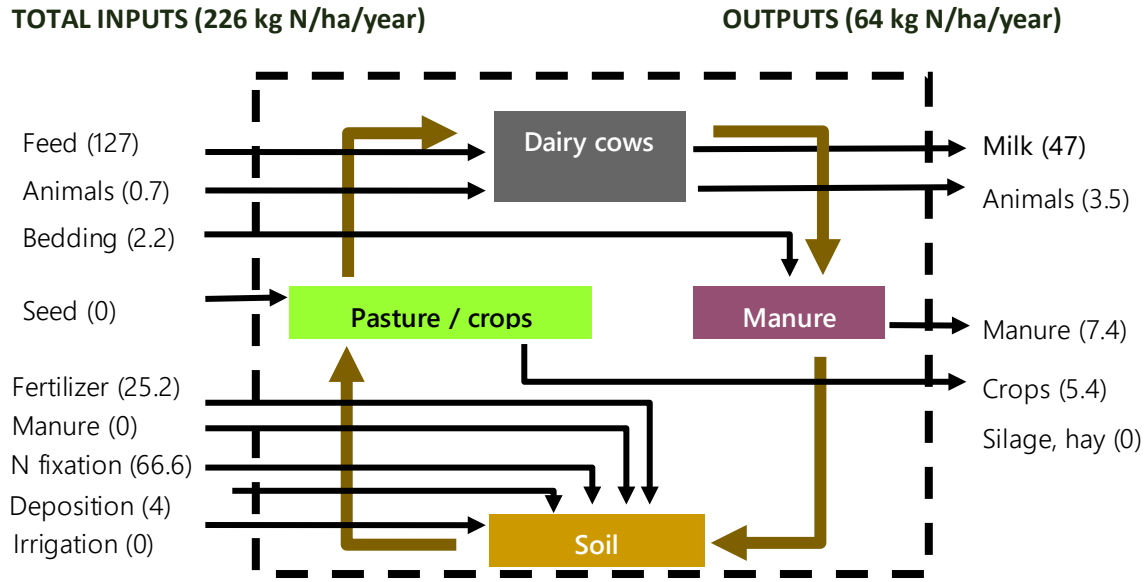


Figure 9.11. Whole-farm nitrogen budget for USA high-intensity dairy system with cropping, as an illustration of Type 5. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Table 9.18. Indicators for farm nitrogen budget, together with indicators related to intake, milk and excretion for USA high-intensity dairy farm, as an illustration of Type 5.

Whole-farm nitrogen budget						
Nitrogen Use Efficiency		**N Surplus**		**Milk Production N Surplus**		
28.1%		**162 kg N/ha/year**		**12.8 g N/l**		
Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Maize silage	10	1.42	142	Herd	7323	L/herd/day
Grain concentrate	5	2.34	117	Cow	28.2	L/cow/day
Alfalfa hay	5	3.40	170			
Byproducts	3.7	3.84	142	Milk N concentration	0.51	N%
				Milk N exported	147	g N/cow/day
Total N (TMR)			571	**Manure N Produced**		
Milk - NUE	25.8%			Cow per day	424	g/cow/day
				Cow per year	155	kg/cow/year
				Herd per year	36.5	tonne/herd/year

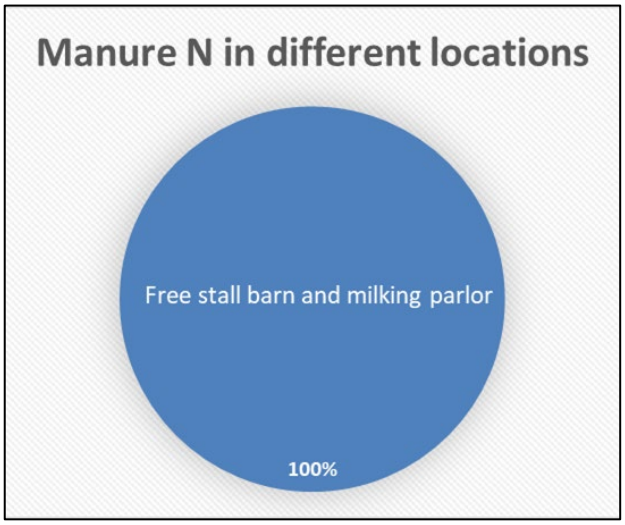


Figure 9.12. Share of manure (including dung and urine) that is excreted in different locations of a USA high-intensity dairy farm (Type 5). (Original graphic produced for this document © UKCEH, 2026.)

9.7 International dairy typology 6: Landless housing systems



Image 52. Shijiazhuang, China, free stall barn. Image courtesy of C Gourley.



Image 53. Shijiazhuang, China, manure storage. Image courtesy of C Gourley.

Table 9.19. Characteristics of international dairy typology 6.

Landless housing systems	
Typical farm system characteristics	Industrial feedlot, usually 200 - 600 lactating cows, situated near large urban markets.
Countries / regions generally applicable	China
Typical primary feed sources and quality	Feed consists mainly of alfalfa hay, grass hay, corn silage and concentrates, which are purchased from overseas or domestically. Most industrialized dairy farms use a total mixed ration and advanced reproduction and health management technologies.
Typical housing and confinement	Cows are usually housed in free-stall open-air barns.
Typical manure management	Slurry manure is scraped from concrete surfaces into open storage ponds. Sieve or screw press separator systems are sometimes used to separate solid and liquid components. Solid manure fractions are reused as bedding materials. Liquid fractions may be pumped to neighbouring agricultural land uses or discharged into waterways or treatment ponds.
Typical crop and pasture management	There are no associated cropping systems, as the dairy systems are essentially land-less.
Common opportunities to improve NUE	Better balanced dietary intakes of N; improved collection and storage of excreted N; Reuse of manure N; Closed manure storage and application systems.

Table 9.20. Details of Chinese dairy farm used as case study.



Image 54. Shijiazhuang, China, solid manure storage. Image courtesy of C Gourley.

Chinese Industrial feedlot with full confinement	
Herd size	250 lactating cows
Average cow weight	550 kg
Milking area	Not relevant
Stocking rate (cows/ha)	Not relevant
Cow milk production per year	7,500 L
Milk from imported feed:	1,475,330 L
Milk from home grown feed	None
Purchased feed to total feed ratio	100%
Proportion manure land applied	50%

Data sources:

- Industry average milk production and feed intakes for land-less dairy production in China (Tier 1 data).
- International feed and milk N concentrations (Tier 1 data).
- See: Zhang N, *et al.* (2017); Bai ZH, *et al.* (2013).

Whole-farm nitrogen budget:

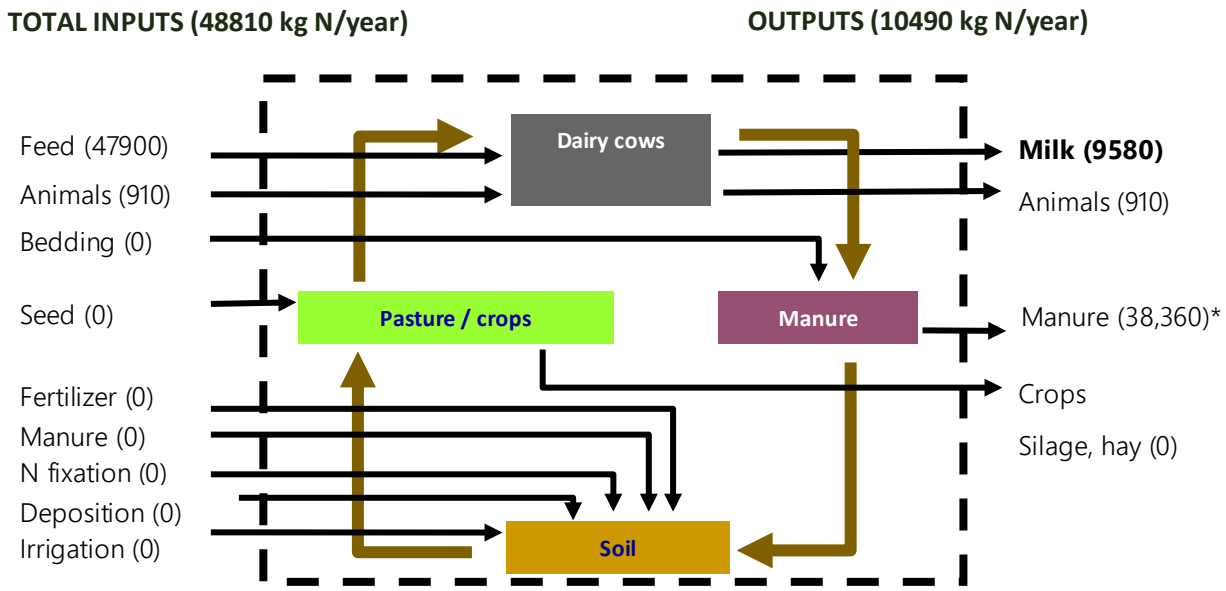


Figure 9.13. Whole-farm nitrogen budget for Chinese landless dairy system, as an illustration of Type 6. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

*High export of collected manure (>85%) but high N losses (~30-50%) of excreted N through volatilization and N_2O emissions from hard surfaces and composting of solid manure fractions.

Table 9.21. Indicators for farm nitrogen budget, together with indicators related to intake, milk and excretion for Chinese land-less dairy system, as an illustration of Type 6.

Whole-farm nitrogen budget indicators						
Nitrogen Use Efficiency		**N Surplus**		**Milk Production N Surplus**		
21.5%		**38,360 kg N/year**		**20.4 g N/l**		
Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Maize silage	10	1.36	136	Herd	5150	L/herd/day
Grain concentrate	5	2.24	112	Cow	20.5	L/cow/day
Alfalfa hay	5	3.20	160			
Byproducts	4	2.56	102	Milk N concentration	0.53	N%
				Milk N exported	110	g N/cow/day
Total			510	Manure N Produced		
Milk - NUE	21.3%			Cow per day	402	g/cow/day
				Cow per year	147	kg/cow/year
				Herd per year	36.6	tonne/herd/year

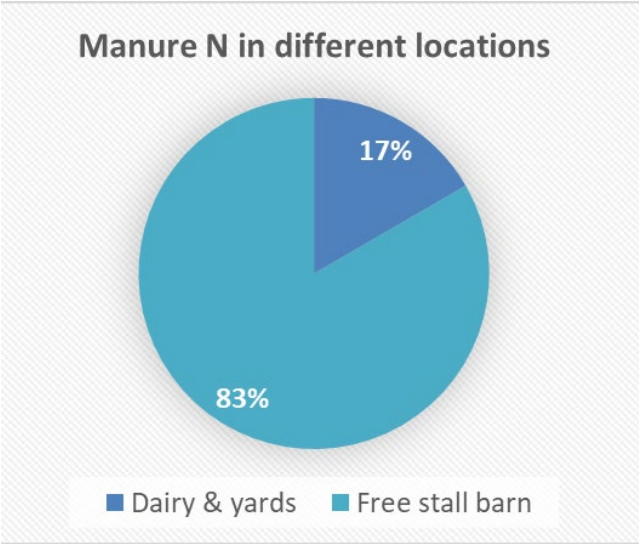


Figure 9.14. Share of manure (including dung and urine) that is excreted in different locations of a Chinese land-less dairy system (Type 6). (Original graphic produced for this document, © UKCEH, 2026.)

9.8 International dairy typology 7: Collective farm systems with centralized feed and manure management



Image 55. Hokkaido, Japan, manure storage. Image courtesy of Y Uchida.



Image 56. Hokkaido, Japan, Timothy grass forage. Image courtesy of Y Uchida.

Table 9.22. Characteristics of international dairy typology 7.

Collective farm systems	
Typical farm system characteristics	A collective system consisting of approximately 20 farms, with a centralised feed and manure management. The manure is managed by a company running biogas plants, while agronomy and crop production on the land owned by each farm, and a total mixed ration (TMR) system, is also managed independently of the farmers by a specialized production company. Each farmer buys TMR from the production company, enabling the dairy farmers to specialize in animal management, feeding and milking.
Countries / regions generally applicable	Japan
Typical primary feed sources and quality	More than half of the feed (energy basis) is concentrated feeds imported, particularly from overseas. Home-grown forage comprises of dent corn and grass silage (Timothy and/or Orchard grass). Sometimes locally available feed sources such as beat pulp are used as supplements.
Typical housing and confinement	Free stalls system with solid roofs (to cope with snow).
Typical manure management	Manure, mixed with bedding materials (often wheat straw or tree bark), is collected and centralized at biogas plants.
Typical crop and pasture management	Half corn and half timothy grass, both used for silage production, are harvested by the total mixed ration (TMR) centre (not by the farmers). The fertilizer application and harvest timings are also planned and applied by the TMR centre.
Typical crop and pasture fertilization	The anaerobic digestate from the biogas plants is the main fertilizer. Chemical fertilizers are also used but depends on existing fertility of individual paddocks.
Common opportunities to improve NUE	High stocking rate and high reliance on imported feed results in high manure loads requiring collection as feedstock for biogas production. The capacity of the biogas plants and size of the TMR centre influences the number of cows that can be supported. There is an imbalance between manure N produced and limited land area available for crop production.



Image 57. Hokkaido, Japan, Free stall barn. Image courtesy of Y Uchida.

Table 9.23. Details of Japanese collective dairy system used as case study

Japanese collective of 20 dairy farms	
Herd size	2,606 lactating cows
Average cow weight	500 kg
Stocking rate (cows/ha)	2.0 cows/ha
Total collective farm area	1,313 ha
Cow milk production per year	10,164 L
Milk from imported feed:	14,262,555 L
Milk from home grown feed	12,224,024 L
Proportion of feed imported	52%

Data sources:

- Factual survey data, including milk production, feed intakes and N content, and fertilizer inputs for collective dairy farming in Northern Japan (Tier 3 data).
- Biological N fixation and atmospheric deposition estimates from national studies (Tier 2).
- See: Toda M, *et al.* (2020). Nitrogen balance and use efficiency on dairy farms in Japan: a comparison among farms at different scales. Environmental Research Communications 2, 125001. 10.1088/2515-7620/abce4a.

Whole-farm nitrogen budget:

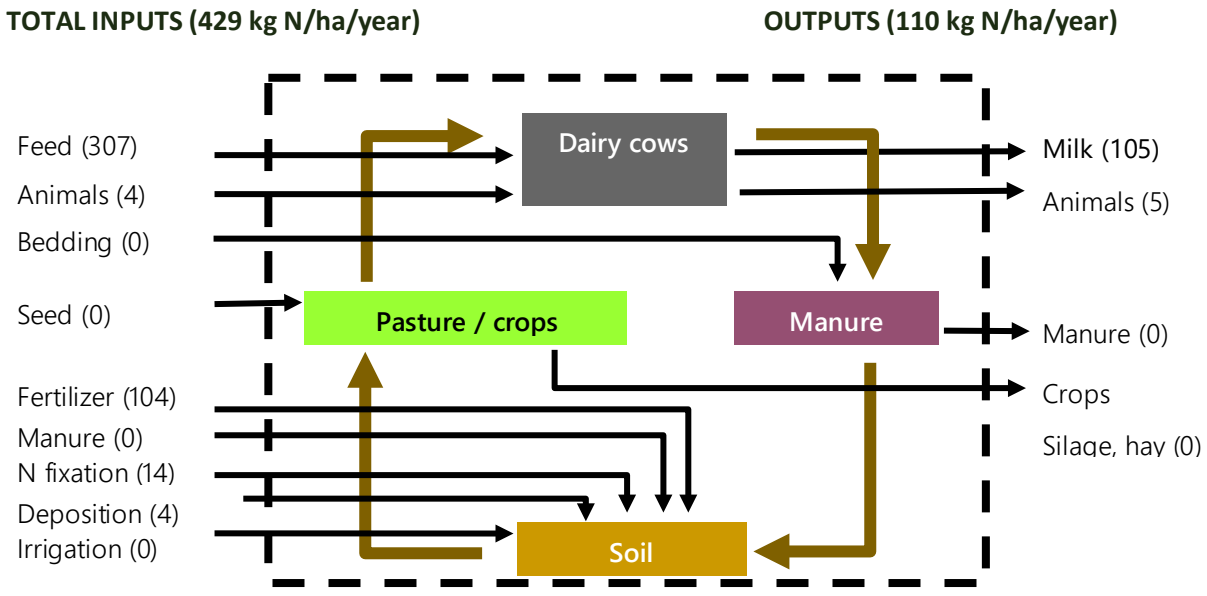


Figure 9.15. Whole-farm nitrogen budget for Japanese dairy farm collective system, as an illustration of Type 7. The values shown are annual nitrogen flows expressed as kg N/ha/year. (Original graphic produced for this document, © UKCEH, 2026.)

Note: Collected manure is reapplied to crops and grassland as slurry and digestate ~300 Kg N/ha

Table 9.24. Indicators for farm nitrogen budget, together with indicators related to intake, milk and excretion for Chinese land-less dairy system, as an illustration of Type 7.

Whole-farm nitrogen budget indicators						
Nitrogen Use Efficiency			**N Surplus**		**Milk Production N Surplus**	
25.7%			**319 kg N/ha/year**		**15.5 g N/l**	
Nitrogen intakes, milk N exports, NUE_{Milk} and manure N excreted						
Dietary Intake (DM)				Milk Production		
Feed type	kg/cow/day	N%	g N/cow/day			
Concentrate	10	3.2	320	Herd	72,600	L/herd/day
Silage	11	1.6	176	Cow	27.9	L/cow/day
Hay	1	1.6	16			
By-products	1	1.6	16	Milk N concentration	0.53	N%
				Milk N exported	147	g N/cow/day
Total			528	**Manure N Produced**		
Milk - NUE	27.8%			Cow per day	381	g/cow/day
				Cow per year	139	kg/cow/year
				Herd per year	362	tonne/herd/year

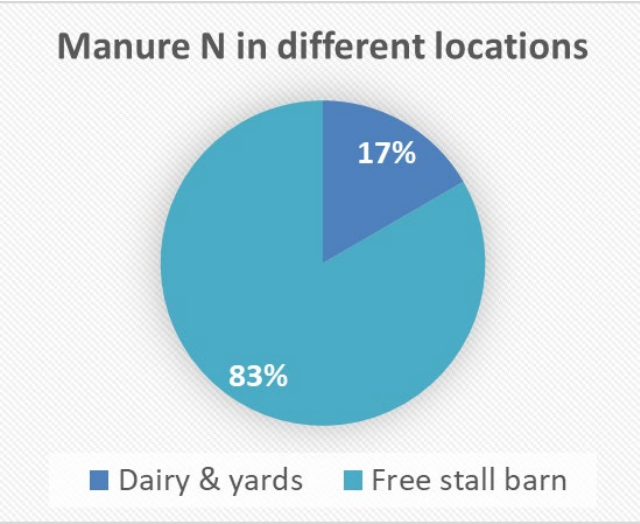


Figure 9.16. Share of manure (including dung and urine) that is excreted in different locations of a Japanese collective dairy system (Type 5). (Original graphic produced for this document, © UKCEH, 2026.)

Chapter 10: Recommendations for policy, industry and farmers

The low utilisation of nutrients in many agricultural systems creates a global challenge with nutrient excesses and environmental degradation of land and water ecosystems and the atmosphere (Sutton *et al.* 2013). This is particularly the case for dairy production systems where N fluxes may be large and the efficiency of N use relatively low at the whole-farm and component level.

Dairy N efficiency indicators can therefore provide valuable insights into the productivity and environmental performance of a broad range of dairy production systems. However, contrasting environmental or policy pressures and differences in N management of dairy system typologies require specific interpretation of whole-farm and within-farm N efficiency indicators. The best indicator to use depends on the economic or environmental goals that are being addressed. Table 31 provides an overview of commonly used N efficiency indicators and their main purpose.

Table 10. Overview of commonly used N efficiency indicators and the key purpose they serve.

Indicator	How to estimate	Key purpose
Whole-farm nitrogen use efficiency	= [Σ (N farm outputs) / Σ (N farm inputs)]	Assess economic efficiency of N use
Whole-farm N surplus (or deficit)	= Σ (N farm inputs) − Σ (N farm outputs);	Assess risk of environmental N loss
Crop nitrogen use efficiency	= [Σ (N crop N harvested) / Σ (N inputs to crop production)]	Assess within-farm N inefficiencies to prioritise opportunities for management improvement
Animal nitrogen use efficiency	= [Σ (N milk or meat N outputs) / Σ (animal N intake in feed)]	
Milk production N surplus	= N surplus / total litres of milk produced	Assess risk of environmental N loss per unit economic output

Nitrogen budgets are a useful tool for nutrient management planning and for estimating the N use indicators. Nitrogen budgets are appreciated by farmers and policy makers for the accessible information and integration of farm-based data into clear outputs that they provide. For farmers and advisors, this means that N budgets should continue to rely on reliable, simple and easy to collect data. The development of standardised 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.

Individual indicators need to be seen in relation to other indicators. For example, whole-farm NUE needs to be complemented with within-farm N flows, transformations and loss pathways. **This improves the ability to identify where key N management improvements can be made that are within the control of farmers.** Many N management decisions also have a direct impact on farm profitability. More information on the costs and benefits associated with nutrient management decisions would provide an increased incentive for farmers to improve N management practices. This is

becoming more attainable as there is often increased access to analytical laboratories and in situ tools to help manage and document farm N fluxes.

Nitrogen budgets and NUE indicators are also very useful when multiple stakeholders are involved in the broader aspects of dairy farming (e.g., farmers, milk companies, biogas/feed factories, consumers etc) as they provide a simple means of connectivity through the supply chain.

Nitrogen budgets, while relatively simple and providing integrated outcomes, have uncertainties due to limitations and coarseness of available data and biases and errors. Book values for nutrient concentrations in imported feed and manure may not reflect actual concentrations, and sub-samples may have analytical and sampling errors. Assessments often fail to address output uncertainties.

Interpreting N balance information and internal N use efficiencies requires a contextual understanding of the farming system and environmental conditions. Rather than aiming for 100% nutrient efficiencies or no net surplus, potential nutrient management standards for the whole farm or specific components (e.g., feed nutrient use efficiency, manure collection, crop nutrient use efficiency) are more appropriate. Standards can be set politically or based on modelled expectations and experimental work (Figure 5) but should be realistically defined by best practices from a larger data set of dairy farms with similar typology. Farm N budget information should therefore be presented as actual versus potential performance to facilitate effective interpretation and benchmarking against similar farms and inform appropriate policy standards. It must also recognize that best practices may evolve with time, as developing innovation provide opportunities for higher efficiency and lower waste of nitrogen resources.

The output of N from dairy systems is usually dominated by milk exports, and hence whole-farm level NUE (expressed per cow) is largely dependent on the milk productivity per cow. Grazing systems generally have lower whole-farm NUE due to lower milk yields, as grazing animals require extra energy when actively sourcing forage. In intensive confinement systems, a greater proportion of feed energy is available for milk production, and dietary intakes better balance CP (Mu *et al.*, 2017). Pastoral grazing-based systems generally require more, land but rely less on external concentrate feed N and fertilizer N due to manure N inputs directly deposited on to pasture soils without staged losses in the manure handling train of confined operations (Aarons *et al.*, 2020).

Milk production per cow tends to be similar between specialized landless systems and market-oriented dairy-crop systems. The density of dairy production generally has a positive impact on the whole farm NUE, provided that N is managed appropriately for crop production. Consequently, overall whole-farm NUE is largely influenced by the density of dairy production per hectare of cropland, as well as the utilization of home-grown feed. The effective management of manure N for home-grown crop production is therefore important to enhance whole-farm NUE, given that NUE in crop production is typically greater than the utilization of N at the dairy herd level.

Increased home-grown feed, which relies on manure produced on the farm instead of bought-in mineral fertilizer, should also lead to higher NUE in the market-oriented dairy-crop systems. High input and specialised dairy systems can have a high proportion of excreted N collected and transported to nearby farmland (Gourley *et al.* 2012b), which usually means a much higher whole-farm NUE than in other systems. This further indicates that the system boundary has strong impacts on understanding the NUE of different dairy production systems.

We conclude that whole-farm and within-farm assessments of N use, including for cow milk production, dietary N intakes, manure N management, and crop N inputs, can be used successfully across different dairy systems internationally to provide an appraisal of current N use efficiencies, and assist farmers and advisors to identify opportunities for improving farm N management.

The implementation and interpretation of NUE indicators needs to recognise specific environmental and economic challenges and across the broad range of dairy production systems; specifically addressing the very low per cow milk yields achieved in low-input traditional systems, managing N intakes within more specialised systems, and the need for enhanced capture and redistribution of manure N across all systems. Ultimately, these indicators should be used to monitor N management practices, so assessing progress against trends rather than set values is important.

Dairy NUE indicators should be used to determine industry-based N use efficiency benchmark values that align with the agro-climatic context in which the dairy systems operate and the economic and environmental goals they are aiming to achieve. We suggest that a broad application of N budgets, N surplus and N use efficiency indicators would help set appropriate policy goals and drive innovations in consideration of typologies. This will help set appropriate international practices in support of dependable food supplies and clean environment.

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Dairy production is a crucial source of food and income for millions of farmers worldwide. Nitrogen is a primary nutrient input in dairy systems, enhancing feed and milk production, but inefficient nitrogen use and cycling results in environmental pollution.

Standardizing nitrogen budgets, performance indicators and reporting frameworks can benchmark dairy systems and enable the identification of best practices and environmental improvements. This INMS Guidance Document offers guidance on sustainable nitrogen management and nitrogen use efficiency indicators for the global dairy industry.



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