CIEL

WHY NITROGEN MATTERS IN LIVESTOCK PRODUCTION

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1. Preface

CIEL recognises that a key part of its mission to facilitate the delivery of sustainable and circular food systems is to emphasise the critical value of nitrogen (N) in livestock production. By exploring how N cycles through the system, interacting with the atmosphere, soil, water, plants, animals and microbes, CIEL seeks to highlight the balance of N in livestock production and empower informed decision making to reduce N losses.

Nitrogen is fundamentally important to the protein nutrition of all living organisms, and N fertilisers have been one of the cornerstones of modern agricultural productivity gains. However, the same intensification of modern agriculture that has brought about increases in productivity has also led to negative environmental impacts through excessive N losses from the system. In 2020, agriculture was responsible for 69% of the UK's total nitrous oxide (N_2O) emissions – a potent greenhouse gas (GHG) with 273 times the warming potential of carbon dioxide (CO_2). Nitrogen also contributes to air pollution through ammonia (NH_3) emissions and can pollute our waterways through nitrate (NO_3^-) leaching, underscoring its potential to influence negative changes in our natural environment.

To reduce the environmental impact of N in livestock production, we first need a broader understanding of N's interaction with the environment. This report takes a deep dive into the 'nitrogen cycle', explaining how agricultural practices shape the way N moves through this natural cycle and behaves in the atmosphere. Not only will this inform debate about how best to manage nitrogen use efficiency but also how N pollution could be mitigated. It is the whole cycle, and the roles N performs in its various forms, that needs to be understood if we are to integrate the understanding of this cycle into sustainable food systems of the future. Our goal should be to maximise value across nutritional quality (for animals and humans), environmental enhancement and resource use efficiency.

CIEL is producing another relevant report focusing on the significance of protein quality. We recommend you read that as well, due to the fundamental link between N and protein in terms of nutritional quality and the efficiency of food production.

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2. Executive summary

Nitrogen cycles through the atmosphere, soil, water, plants, animals and microbes; a natural cycle that underpins production of the food upon which we all depend. Nitrogen is an essential element for protein nutrition but is also present in a powerful GHG (nitrous oxide), an air pollutant (ammonia) and a water pollutant (nitrate). Nitrogen is continuously transformed between organic and inorganic forms through different biological processes.

Nitrogen can have positive or negative impacts depending on its form and where it occurs. For example, protein is created by adding N to carbohydrate substrates but if not digested and absorbed by livestock it can lead to emissions from manures. Also, nitrate is an effective fertiliser, but can have negative effects when lost into watercourses.

While plants and soil microbes transfer some N to the environment due to intrinsic inefficiencies, they can capture N from the environment and incorporate that into protein – something livestock cannot do.

Livestock play a key role in the production of high-quality protein for human nutrition, such as meat, milk and eggs. No other proteins are so well suited to human nutrition in their natural form, and livestock can produce this from low-quality 'feedstocks'. Ruminants are the only livestock species with the ability to gain protein from inorganic N in their diet through the symbiotic relationship they have with rumen microbes. Upgrading of nutritional value is why livestock were domesticated and why ruminants in particular play a key role in agriculture.

During conversion of N in livestock feed to meat, milk and eggs, intrinsic inefficiencies lead to N being transferred to the environment through faeces and urine as nitrous oxide or ammonia. Nitrogen losses from livestock are also influenced by other factors including dietary N supply, production level, stage of growth, health and genetics.

Animal manures should not be considered as waste as they can be used to improve soil health and fertility, replacing artificial N fertiliser to a varying extent. Appropriate management to reduce N losses from manure will increase the capacity to do this. Use of manures in this way reduces the carbon footprint costs associated with the production and application of artificial fertiliser.

Nitrogen losses can be minimised with good management. Approaches to assessing nitrogen use efficiency (NUE) can be quantified at the farm level or as components of the farm system (e.g. animal or crop). It is recommended that NUE should be reported together with N surplus (as a proxy for N loss to the environment) and N output in products (as indicator of productivity).

Inefficient use of N on farms is a result of both fundamental biological limits and attitudes to risk and genuine waste. One example is the use of 'safety margins' as an insurance policy when formulating diets or determining fertiliser application rates. Major N inefficiencies can be minimised through improved information and better decision support systems, by understanding the factors that influence N losses at different points, animal and plant productivity, and the need for N inputs. Economic considerations should be broadened to consider other dimensions of value from a sustainability context.

To improve NUE in livestock farming we should:

- Think in terms of nutrient circularity, with the N cycle being a key framing point
- Use alternate feed options that minimise N losses without reducing N captured as protein in highly nutritious food products
- Implement systems to capture and retain N, including those that can enhance growth of feed crops. Animal manures have an important role here
- Use smart, data-led systems to quantify N resources, monitor changes over time and inform active management of N resources

We have an urgent need for innovation in the following key areas in order to be able to manage N resources more effectively:

- Measurement of N in key pools with sufficient accuracy – in soil, for example
- Accurate assessment of changes in N pools (inputs, outputs, transfers between) to model these more effectively
- Define a common scale of value for sustainable management of N resources that accounts for: nutritional value as protein, fertiliser value for plant productivity, potential value of N stores in the landscape and pollution impacts

An understanding of the N cycle provides a better perspective of the role livestock play in agriculture. While increasingly subject to scrutiny in terms of their environmental impact, livestock offer enormous potential as an opportunity – or even a catalyst – to promote better environmental stewardship and sustainable agricultural practices while contributing to food security.

3. Introduction

Nitrogen makes up the majority (78%) of the earth's atmosphere and cycles in various forms between the atmosphere, plants, soils, water, animals, microbes and humans **(Figure 1)**. Nitrogen is an essential element in the production of proteins and DNA found in plants and animals.

Nitrogen is largely lost from agriculture and food systems by either leaching from soils into watercourses as nitrate (NO_3^-) or as gaseous emissions. The key emissions from agricultural systems releasing gaseous N to the atmosphere are nitrous oxide (N_2O), a GHG, and ammonia (NH_3), an air pollutant.

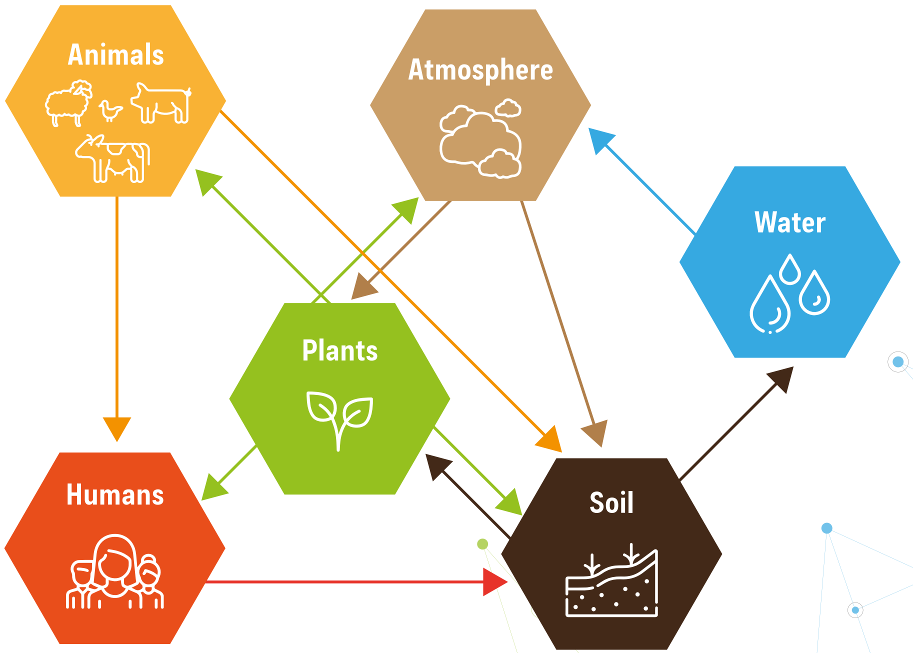


Figure 1. Simple diagram of nitrogen dynamics between the atmosphere, plants, soils, water, animals and humans. Microbes play a key role in all these pathways

The amount of N inputs on agricultural land is regulated under the Nitrates Directive. This directive aims to prevent excess NO_3^- build-up in soils, which leads to NO_3^- leaching from soils into watercourses and negatively impacts water quality. Areas of land near watercourses with high NO_3^- levels may be designated as Nitrate Vulnerable Zones (NVZs), and restrictions on NO_3^- application rates are enforceable.

The UK Government's Climate Change Act (2008) sets an ambitious target to achieve Net Zero GHG emissions by 2050. To meet this target all sectors must radically reduce their GHG emissions. Since 1990 (the baseline year for GHG emissions), UK agriculture has reduced its emissions by only 16%[1]. Nitrous oxide is a potent GHG, which has a global warming potential (GWP) 273 times greater than carbon dioxide (CO_2) and around 10 times greater than enteric methane (GWP of 27.2) over a 100 year period. Agriculture contributes 69% of total N_2O emissions in the UK.

The Clean Air Strategy 2019[2] outlined the UK's plans to tackle air pollution from several sources, including agriculture. Ammonia negatively impacts sensitive habitats and reacts with other gases in the atmosphere to form particulates which are harmful to human health. The UK is committed to a 16% reduction in NH_3 emissions by 2030 relative to 2005 levels. Agriculture accounts for 87% of NH_3 emissions in the UK so reducing these emissions will have to be largely driven by the sector. Progress in improving air quality is both uncertain, due to a lack of evidence, and slow, due partly to doubt about the efficacy, cost and consequences of improvement measures.

Modern farming practices have increased reliance on artificial N fertiliser to increase crop yields, including feed and forage crops for livestock. However, the manufacture of artificial N fertilisers produces GHGs, and a proportion of the N is emitted to the atmosphere (as N_2O or NH_3) or lost through leaching or runoff after application.

This report aims to explore N cycling in livestock production systems, highlighting the roles of different forms of N, and where losses occur from the cycle. It will:

a. Describe the forms of N in livestock nutrition, and the importance of protein N in human and animal nutrition
b. Describe how N cycles through livestock production systems and where losses occur
c. Discuss current approaches to quantifying NUE

4. Nitrogen in human and animal nutrition

Proteins are built from 20 amino acids which contain carbon, hydrogen, oxygen, nitrogen and two also contain sulphur. Most microorganisms and plants can synthesise all 20 amino acids, but in mammals (including humans) around half of the amino acids (termed 'essential amino acids') can only be obtained from protein consumed in food or, in the case of ruminants, synthesised by microorganisms in the rumen.

Different amino acids contain different amounts of N, but protein in most animal feeds contains approximately 16% N. Therefore, nutritionists routinely quantify crude protein (CP) in feeds as N/0.16, or N x 6.25. Nitrogen is also a component of other biomolecules, including the bases that make up nucleic acids, and ultimately animals and humans must also obtain this N from food.

5. Nitrogen cycling

Nitrogen is continuously transformed between organic (carbon-containing) and inorganic (containing no carbon) forms through different biological processes. These cycle between the soil, atmosphere and plants; some of the key processes are described in **Figure 2**.

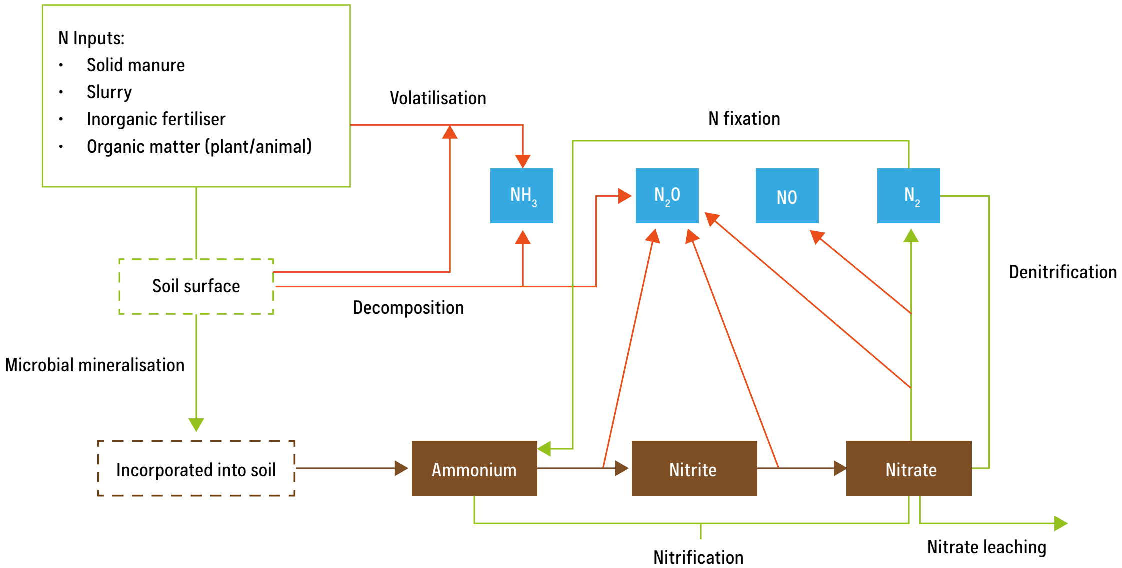


Figure 2. Key processes for nitrogen transactions between fertilisers, manures, soil and the atmosphere. N – nitrogen, N_2O – nitrous oxide, NO – nitric oxide, N_2 – atmospheric nitrogen

5.1 Nitrogen inputs

Nitrogen is added to grasslands and crops either in organic matter (natural material from solid animal manure or slurry, or the remains of plants or animals) or as synthetic inorganic fertiliser. It is also captured from atmospheric N by some soil microorganisms (e.g. rhizobium that colonises roots of legumes such as clover) in the process of biological N fixation.

The main organic forms of N that enter this cycle from livestock are undigested dietary protein in faeces, urea in urine (mammals) and uric acid in poultry faeces. Other inputs from livestock include N in blood and bone meal used as fertiliser (a by-product of meat processing and dead stock).

5.2 Ammonia volatilisation

Ammonia is generated from animal manures when bacterial urease (an enzyme synthesised by a wide variety of plants, fungi and bacteria) in faeces reacts with urea from urine. Ammonia is highly volatile and easily emitted to the atmosphere from manure in animal housing, storage or during field application. It is also emitted from ammonium-containing inorganic fertiliser. In the UK, NH_3 emissions from these processes were estimated at 226 thousand tonnes of N in 2020[3]. This represents 87% of total UK NH_3 emissions. The amount of N lost as NH_3 from organic manures depends partly on methods of storage and application (e.g. using a splash plate to apply to fields results in more volatilisation than a trailing hose).

5.3 Mineralisation

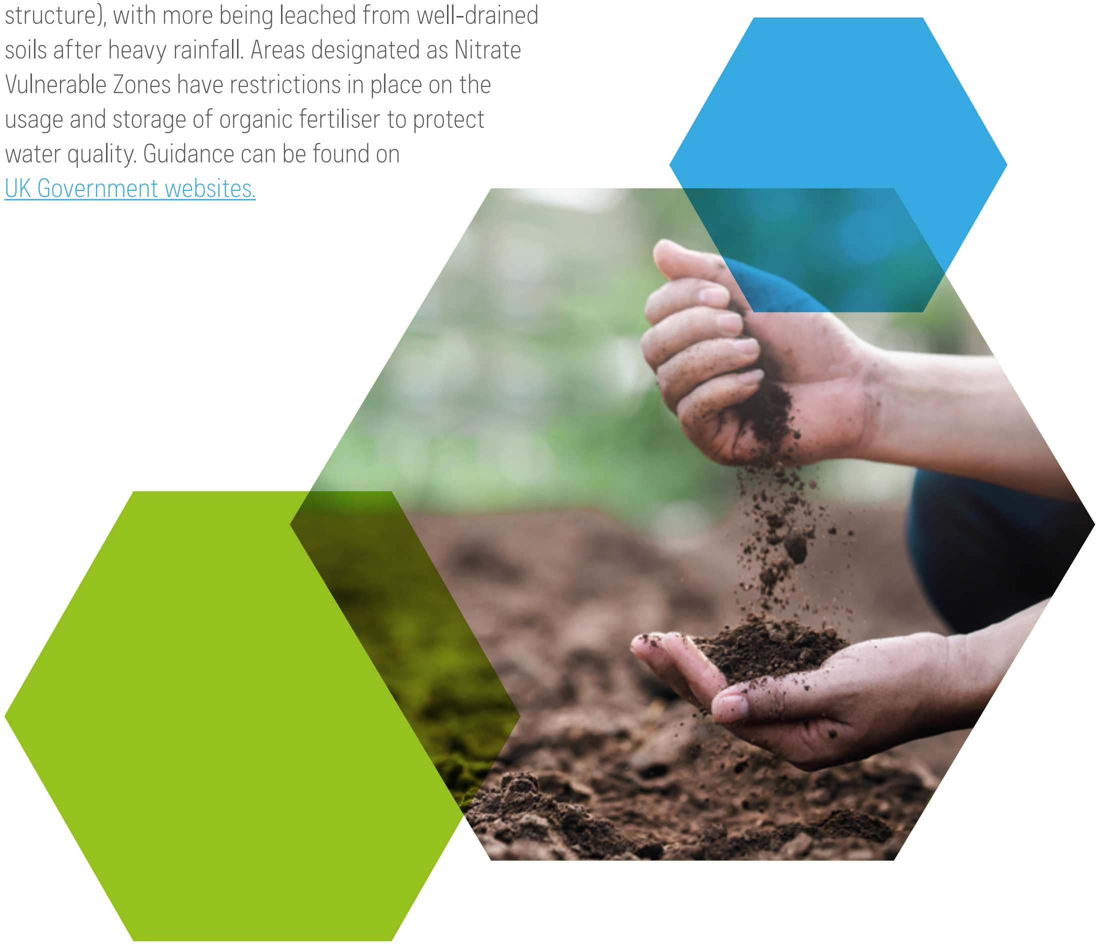
Plants take up inorganic forms of N, so N in organic matter must first be converted to inorganic N by microbial mineralisation – the process of soil microbes decomposing organic matter to form ammonium. During this process some N is emitted to the atmosphere as NH_3. Between 95% and 99% of the N in soils is within organic matter, but only 2% of N in soil organic matter is mineralised each year. While most fresh organic matter in the soil is usually broken down relatively quickly (months to years), material with a high carbon-to-nitrogen ratio (such as lignin, a molecule important in providing structure to plants) is difficult for microbes to utilise as a food source and mineralise, locking such N in the soil for long time periods (around 180 years).

5.4 Nitrification and denitrification

These processes relate to the production or loss of NO_3^-. In well-drained soils, ammonium is converted to NO_3^- by nitrifying bacteria. Where there is insufficient demand for NO_3^- (e.g. bare soil with no living plant roots to take up NO_3^-), it will accumulate in the soil leaving it vulnerable to loss by leaching. In poorly-drained soils, or in wet conditions where oxygen is not available, denitrifying bacteria convert NO_3^- to nitrogen gas. At each step in the nitrification and denitrification processes N is released to the atmosphere as nitric oxide, nitrous oxide or nitrogen gas. Denitrification results in large losses of N from agricultural soils (up to 59%)[4].

5.5 Leaching

Nitrate is soluble and can easily leach from soil into watercourses, but ammonium, dissolved organic N (e.g. proteins, amino acids and urea) and particles of organic matter can also be lost through leaching or runoff. How much N is leached each year varies widely and depends largely on whether there is more plant-available inorganic N in the soil than the crop can utilise, and on rainfall patterns (as well as soil type and structure), with more being leached from well-drained soils after heavy rainfall. Areas designated as Nitrate Vulnerable Zones have restrictions in place on the usage and storage of organic fertiliser to protect water quality. Guidance can be found on UK Government websites.



5.6 Nitrogen immobilisation

As living organisms, microbes also require N, and N can be locked in the microbial biomass. When microbial cells die, they become part of the soil organic matter and then this N can be remobilised in the cycle. Nitrogen typically remains in soil microbial biomass for around two years[5].

5.7 Plant uptake of nitrogen

Plants take up NO_3^- and ammonium through their roots. Here, nitrates are converted to ammonium before being used to synthesise amino acids to form protein and other organic compounds containing N that the plant requires. N-fixing bacteria convert atmospheric N into ammonium and plants such as clover with a symbiotic relationship with these bacteria can benefit from this additional source of N.

Nitrogen use efficiency (NUE) by growing crops (including grasslands) is defined as N uptake divided by the amount of N applied as manure and/or fertiliser. Crop NUE is affected by the rate of N loss from the soil (related to soil type and rainfall) and manure or fertiliser use (type, amount, timing and application method). Inhibitors can be added to fertilisers or manures to reduce N losses and improve NUE. The amount of manure N that is quickly mineralisable (and so at greater risk of emission to the atmosphere or leaching) differs between animals, generally decreasing in the order poultry (21%) > pig (19%) > ruminant (13%)[6].

However, this varies depending on dietary protein supply, protein quality and the balance between feed energy and protein. For example, dairy cattle slurry can range from 2% to 19% mineralisable N.

Nitrogen captured by plants in this cycle can have several fates:

a. If the crop is intended for human consumption, some N is lost from the cycle (around half of human consumed N in the UK is returned as fertiliser; three to four million tonnes sewage sludge per year containing ~40 kg N / tonne dried sludge[7])

b. It is returned to the soil as crop residue and continues in the cycle

c. It is consumed by livestock and its fate is then decided by the digestive and metabolic efficiency of the animal

6. Nitrogen cycling in livestock systems

6.1 Comparative digestive physiology of monogastric and ruminant livestock

Relative efficiencies of N utilisation in different animal species reflect differences in their digestive physiology and the nature of feedstuffs they ingest. In all species, digestion (breakdown of food into simple molecules) is accomplished by a combination of physical processing (e.g. chewing), enzymes and acids secreted by the animal, and activities of microorganisms harboured in various compartments of the digestive tract. The products of digestion in upper compartments of the digestive tract (principally the stomach) are then absorbed in lower compartments (principally the small intestine).

Crucially, animals do not themselves secrete enzymes capable of digesting cellulose – the major component of plant cell walls and the most abundant carbohydrate on the planet. However, it can be digested by microorganisms present in the digestive tract. Compared with monogastrics, ruminants harbour more cellulolytic microorganisms and their primary site of microbial digestion – the rumen and reticulum – is positioned before the stomach and small intestine. This enables ruminants to utilise both the volatile fatty acids (produced from fermentation of carbohydrates by microbes, these are absorbed across the rumen wall and are the primary energy source for ruminants) and microbial protein produced by digestion and fermentation in the rumen.

6.1.1 Monogastrics

In pigs, as in humans, most digestion is accomplished in the stomach and small intestine (monogastric). Amino acids resulting from digestion of dietary protein are either absorbed in the small intestine or pass to the hindgut (colon and caecum), along with undigested and partially-digested protein. There, they are subjected to extensive microbial metabolism, yielding end-products of NH_3, other N-containing microbial metabolites such as amines and microbial protein. These compounds are generated after the main sites of protein absorption, so are unavailable to the animal, being lost in faeces, or as urea in urine.

Poultry are also classed as monogastric (in the sense of possessing a single chambered stomach where digestion occurs), but the additional presence of a crop and gizzard allows for some physical breakdown of feed in the absence of teeth for chewing. In birds, surplus absorbed N is excreted as uric acid, rather than urea, entering the cloaca before co-excretion from the body with faeces. Uric acid is less soluble than urea and is excreted as a white paste.

6.1.2 Ruminants

Herbivorous mammals, predominantly ruminant species (e.g. cattle, sheep and goats) but also some non-ruminant species such as rabbits, equines and elephants have evolved a range of adaptations to take advantage of the ability of microorganisms to digest plant cell walls. For the purpose of this report only true ruminants, such as cattle and sheep, will be considered as these species make up a large proportion of farmed livestock in the UK and contribute a significant proportion of agricultural emissions. The rumen and reticulum (considered a single compartment, the 'reticulo-rumen') resemble a large vat accommodating complex communities of microorganisms (bacteria, protozoa, fungi and archaea). In cattle, the reticulo-rumen and its contents account for 9-13% of body weight (and around 75% of total weight of the digestive tract and its contents).

Rumination (the cycle of regurgitation from the reticulo-rumen to the oral cavity, chewing and re-swallowing) results in particle size reduction, helping digestion by enzymes produced by rumen microorganisms. In the reticulo-rumen, complex carbohydrates such as starch, hemicellulose and cellulose are digested to simple sugars, from which rumen microorganisms can obtain energy through fermentation. Lignin, a non-carbohydrate component of many plant cell walls, is not digested in the rumen, but profoundly affects the rate and extent of the digestion of cellulose and hemicellulose.

The main pathways of N metabolism in ruminants are depicted in **Figure 3**. Dietary proteins are progressively digested by rumen microorganisms into peptides (short chains of amino acids from digestion of protein), amino acids and, ultimately, NH_3. Some rumen microorganisms can take up these amino acids and small peptides and use them as building blocks for their own proteins. Others – notably many of the bacteria responsible for digesting plant cell walls – use NH_3 as the N source for protein synthesis. In addition to degradation of dietary protein, rumen microorganisms can obtain ammonia-N from fermented feedstuffs such as grass silage, from degradation of urea recycled from the liver into the rumen across the rumen wall or in saliva, or added directly to the diet as a feed material. Indeed, it was demonstrated decades ago that ruminants can be maintained (and can grow and produce milk) for years on diets containing non-protein N but no protein N (see below).

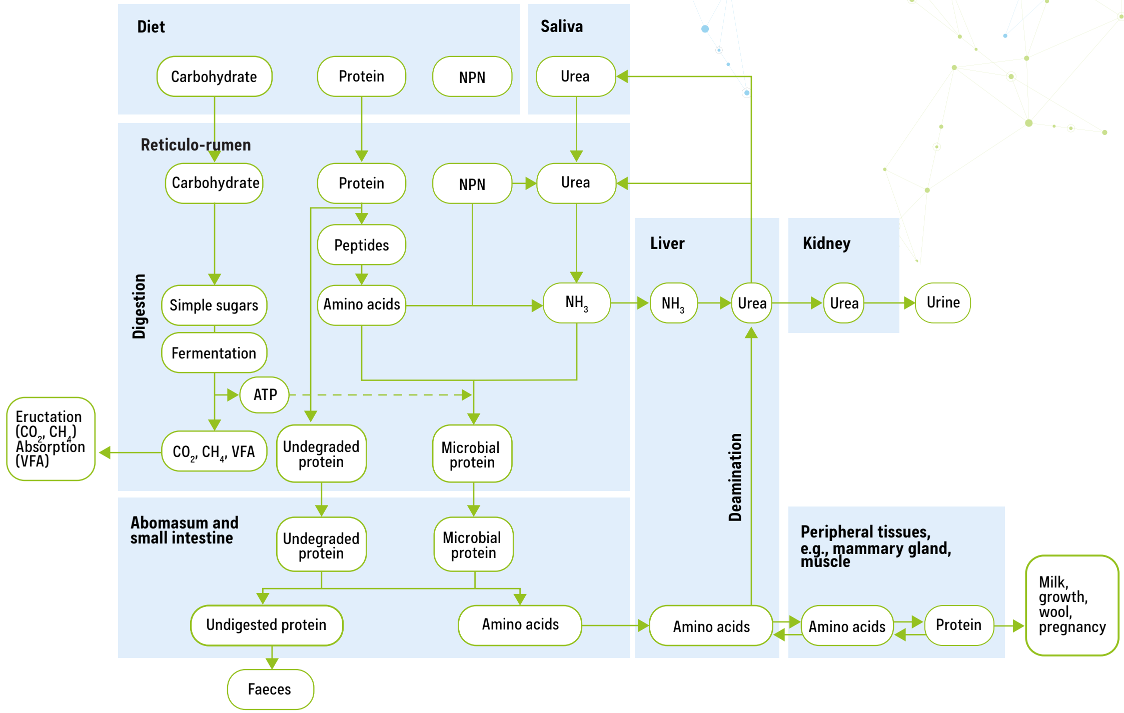


Figure 3. Major pathways of N metabolism in ruminants. Large intestine omitted for clarity. Abbreviations: NPN = dietary non-protein N, including ammonia (NH_3) in silage and N in feed-grade urea. VFA = volatile fatty acids, principally acetic, propionic and butyric

Protein-free diets for ruminants?

A unique feature of ruminants is that they can survive and perform adequately without protein in their diet, as long as they have sources of nitrogen and fermentable energy that rumen microbes can use to synthesise protein. “Will cows on synthetic diets help end world hunger?”, a key paper by Virtanen (1967) describing this phenomenon can be found here.

This is the principle behind feeding straw treated with urea, and why ammonia in fermented feed like silage can be used by rumen microbes to add protein to the diet. For example, a cow may eat less protein than she absorbs at her small intestine, but the microbes are effectively ‘upgrading’ a low-quality diet. However, diets with high levels of high-quality protein may be downgraded by rumen microbes.

Ruminants have evolved to exploit low-quality forage and this is an evolutionary advantage over other herbivores. They turn forage with little nutritional value into highly-nutritious food for humans.

The proportion of dietary protein that is degraded and utilised in the rumen is the result of competition between rate of digestion (generally an inherent feature of the feedstuff) and rate of passage (generally a characteristic of the animal and level of feeding). Most proteins in ruminant feedstuffs are degraded in the rumen, but a proportion will always pass intact (undegraded) to the abomasum (true stomach) and small intestine where they are digested and absorbed. The proportion that bypasses the rumen can be increased by appropriate feed processing methods, such as heat treatment, to produce what is called 'protected protein'.

Rumen microorganisms can only grow and function if they can obtain energy. Under the anaerobic conditions of the rumen, microorganisms obtain their energy by fermenting monosaccharides (simple sugars), derived from the digestion of complex carbohydrates such as starch or cellulose (some energy can also be derived from the carbon skeletons of amino acids and the glycerol in dietary fats). This fermentation co-generates volatile fatty acids (chiefly acetic, propionic and butyric acids) which, absorbed across the rumen wall, constitute the animal's major source of energy. In this way, the energy in consumed feed is shared between the microorganisms (enabling them to grow, provide the animal with protein and continue the work of digestion) and the host animal. To grow microbial protein, the supply of dietary N must be accompanied by energy sources that can be digested and then fermented (fermentable energy).

Feed sources high in fermentable energy for ruminants include forages grazed or harvested at an early stage of maturity, cereals (wheat, barley, and oats) and food processing by-products such as sugar beet pulp and distillers grains. Feedstuffs high in rumen-degradable protein include distillery by-products and oilseed meals such as rapeseed and sunflower meal.

In ruminants, microbial protein grown in, and then passed out of, the reticulo-rumen usually comprises most of the protein arriving at the abomasum. This is then digested and absorbed (in the small intestine) in the same way as in monogastrics. The amino acid profile of rumen microbial protein is generally a better match for the needs of the animal than the amino acid profile of most plant proteins. For example, the amino acid methionine – often found to be limiting to milk protein synthesis – constitutes 2.63% of rumen microbial protein but only 1.30% of grass protein and 1.97% of rapeseed meal protein. Therefore, the degradation of feed protein and the synthesis of microbial protein represents an upcycling in nutritional value.

The nutritional value of metabolisable protein (the sum of digestible microbial protein and digestible undegraded feed protein) depends on its profile of amino acids. This can be optimised by diet formulation (selecting feed protein sources according to their amino acid profile) and the use of rumen-protected amino acids (especially methionine and lysine) as feed supplements.

In summary, the evolutionary adaptation of placing the reticulo-rumen before the animal's own sites of digestion and absorption allows ruminants to reap nutritional benefits from both microbial digestion of plant cell walls and microbial synthesis of high-quality protein.

6.2 Sources of losses of nitrogen in livestock

Nitrogen in faeces comprises undigested dietary protein and nucleic acid, undigested microbial protein and nucleic acid formed in the digestive tract, and sloughed cells and enzymes secreted into the digestive tract by the animal. The simple measurement of apparent N digestibility, i.e. (N intake – faecal N output) / (N intake), is a function of both the true digestibility of dietary protein and the loss of some protein previously synthesised by the animal (and lost to faeces as undigested sloughed intestinal cells and intestinal secretions). For example, in lactating dairy cows, apparent N digestibility ranges from around 55% to 80%, with similar values observed in pigs (56% to 86%).

The other major route of N loss from the animal is urine. The majority of N in urine is urea (between 60% and 90% depending on dietary N intake), accompanied by smaller amounts of other N-containing compounds such as creatinine and hippuric acid. In lactating cows, output of urinary-N is between 20% and 60% of N intake, increasing as protein content of the diet increases. Similar ranges have been observed in pigs.

Urea (or, in poultry, uric acid) is synthesised from amino acids in the liver. The amount of protein present in animal tissues is the net result of continuous processes of protein synthesis and protein degradation ('protein turnover'). Even in non-pregnant adult animals that are not growing or producing milk or eggs, not all the amino acids released during protein turnover are reutilised; some are deaminated in the liver, resulting in an inevitable basal loss of N to the animal. This is why all animals have a maintenance requirement for protein.

Secondly, not all amino acids absorbed from the digestive tract are utilised to make protein, for muscle growth, milk protein synthesis or egg production. This may be due to a shortage or imbalance in the profile of amino acids available at the site of protein synthesis or to hormonal regulation of protein synthesis.

Urea is also synthesised in the liver from NH_3 absorbed from the rumen and large intestine. In ruminants, most of this NH_3 comes from the breakdown of feed proteins by ruminal microorganisms, although there is also direct consumption of some NH_3 in ruminants fed silage. As described above, capture of ammonia-N into microbial protein depends on the release of energy through microbial fermentation of simple sugars obtained from the digestion of complex carbohydrates such as starch or cellulose. Therefore, absorption of NH_3 from the rumen depends on both the amount of feed protein degraded in the rumen and the balance between rumen-degradable protein and rumen-fermentable carbohydrate. Ammonia is toxic to animals even at low concentrations, so its rapid and effective conversion to urea after absorption is an important safety mechanism in metabolism.

In ruminants, not all urea synthesised in the liver is excreted and wasted. Some is recycled to the rumen via saliva or across the rumen wall, where it can be used for further microbial growth. The extent of recycling is very much dependent on the diet. In a low-protein diet of 50g CP/kg dry matter, recycling can be as high as 70% of N intake. However, at higher levels of protein in the diet (200g CP/kg dry matter) the estimate is much lower at just 11%.

6.3 Summary

These principles highlight several opportunities to formulate livestock diets to minimise N losses and maximise NUE. In all livestock species, N losses can be minimised by formulating rations using ingredients with high inherent digestibility (thus minimising losses in faeces), by linking the concentration of dietary protein to that of energy, and by optimising the profile of amino acids in metabolisable protein (thus minimising loss of N as urea in urine in mammals or as uric acid leaving birds as faeces). In addition, for ruminants there is a need to balance the supply of rumen-degradable protein and rumen-fermentable energy. These principles are fundamental to the various ration formulation models used by nutrition advisors around the world.

7. Nitrogen in manures

Urea can be rapidly converted to ammonium and lost as NH_3 during manure collection, storage, processing (e.g. composting) and land application when in contact with urease. Ammonium in manure can also be emitted to the atmosphere as N_2O through the processes of nitrification or denitrification (see section 5.4). Recommendations on how to make the most of manure N to meet crop demand are detailed in the AHDB Nutrient Management Guide (RB209 Section 2).

The proportions of N in urine and faeces vary depending on various characteristics of the excreta and the species. As an example, **Table 1** shows the composition of faeces and urine from dairy cattle. In urine, between 60% and 95% of the total N is present as urea with the remainder constituting a mix of purine derivatives, hippuric acid, creatine and creatinine. When urea is mixed with faeces, which contains urease, NH_3 is produced and released to the atmosphere.

As a proportion of N consumed as feed, on average 20% is emitted from manures as NH_3 across the production process including excretion, collection and spreading[8]. The actual proportion of consumed N emitted varies between products, with chicken meat having the lowest emission (12%), followed by milk (17%), pork (19%), eggs (20%) and beef having the highest (22%). Actual emissions are largely dependent on method of manure management and can be reduced through changes to housing (e.g. low emissions flooring used to separate dung and urine), by covering slurry stores, use of a trailing hose to spread slurry, or rapid incorporation of manure into soil.

When dung and urine are deposited by grazing animals, or when manure or slurry is applied to soil, it is difficult to distinguish between NO_3^- and N_2O that originated from the application or from other N sources in the soil (e.g. inorganic fertilisers or plant residues). However, NO_3^- loss through leaching has been estimated to account for 1-25% of manure-N applied to land, with 1-4% emitted to the atmosphere as N_2O.

Output	Dry matter (%)	Total N g/per kg	Urea % of total N	Protein-N % of total N	Ammonium % of total N
Faeces	10-18	10-17	0	90-95	1-4
Urine	3-4	4-10	60-95	0	1

Table 1. Composition of faeces and urine from dairy cattle

8. How long does the nitrogen cycle take?

In the N cycle, atoms of N take many chemical forms and spend variable periods of time in different N pools. Some N is lost quickly from the agricultural system (e.g. in run-off or as gaseous emissions) while some remains in soil or atmospheric pools for centuries. The half-life (time taken for half of the quantity of N to move to another pool) of some key N pools are given in **Table 2**. The dynamics of these pools can be seen in **Figure 2**.

Pool	Half-life
N_2O (atmosphere)	114 years
NH_3 (atmosphere)	Hours to several days
Soil organic matter N	Months to 180 years
Crops/forages	Days to months
NO_3^- in shallow groundwater	Three to 44 years

Table 2. Half-life of key N pools

9. Quantifying nitrogen use efficiency

9.1 General considerations

Nitrogen resource use efficiency calculated simply as output/input provides a single, easily-interpretable metric (0 to 100%, 'the higher the better') for performance of a system. It can be compared across production units (e.g. farms or individual animals) and across time within that production unit. However, it has several limitations.

Firstly, resource use efficiencies calculated simply as output/input are only meaningful (and comparative) if the system is in a steady state: i.e. the quantity of resource stored within the system is constant. If the resource pool size is increasing, efficiency will be low, while the opposite is true if the resource is being depleted. Changes in pool size can be hard to measure, especially if they occur slowly (e.g. in soils), yet proportionally small changes will be quantitatively important when a pool size is large.

Focusing on one desirable output (food for agriculture) implies that all sources of leakage from the system (the inefficiencies) are of equal value. This may not be the case when several pollutants with different consequences are generated. For carbon, this problem is avoided by placing all pollutants on the same scale (global warming potential over a 100-year period, although the merits of this metric continue to be debated). For N lost from agricultural systems in various forms (e.g. NH_3, N_2O and NO_3^-) there is no such single scale. Focusing on one desirable output implies leakages are collectively of lesser importance than output. Likewise, a focus on mitigation of one form of N pollutant may lead to greater losses in another N pollutant.

In practice, the utility of a metric is influenced by the ease and cost of its measurement. NUE is easier to measure in a lactating dairy cow, where quantities of milk N output and feed N input are easily calculable, than in a growing animal, where N content of bodyweight gain is modelled because it is difficult to measure.

Resource use efficiencies are unitless, but the value and cost of a system also rest in the absolute quantities of desirable outputs and undesirable leaks from the system. Being unitless, the concept of time is also lost. Thus, an efficient system (calculated as output/input) can still generate damaging quantities of pollutants very quickly.

An important general consideration is the boundaries of the system for which NUE is being calculated. Farms can be aggregates of enterprises, while enterprises are aggregates of fields and/or animals. A N-efficient farm can contain both N-efficient and N-inefficient animals, and a N-efficient farming system or region can contain both N-efficient and N-inefficient farms. It is important to consider this when evaluating NUE for any individual unit (e.g. field, animal or farm).

In summary, resource use efficiencies can be useful metrics, but will generally require support from other indicators when used to make management decisions. These considerations can be quantified at the farm level or for animals and crops as components of the farm system.

9.2 Farm level

9.2.1 Metrics

Guidelines for the calculation and use of farm level NUE have been provided in a report by the EU Nitrogen Expert Panel (EUNEP) in 2016. The key metrics are NUE and surplus N.

Equation A

NUE = [Σ(**N output**) / Σ(**N input**)] * 100
where on an annual basis

- **N output** = In produce exported from farm (kg/farmed area) - kg N/ha/unit time
- **N input** = In operating resources & feed (kg/farmed area) - kg N/ha/unit time

Equation B

Surplus N (per animal or per hectare) =
total annual **N imported** – total annual **N exported** in produce

NB: Input/output variables for Equation A may or may not be related to a calendar year and may be used for only one source of N, not whole farm N. Equation B typically refers to whole farm transactions on an annual basis.

There are limitations to this approach because of the implicit assumption that surplus N is not retained (as an increase in soil N or as increased livestock protein mass) and so lost to the atmosphere or watercourses. It also takes no account of a potentially-rapid return of a surplus as an input, for example capture of surplus N excreted by grazing ruminants by growing pasture (**Table 2**).

The EUNEP report recommends that NUE should be reported together with N surplus, as a proxy for quantity of N loss to the environment, and N output in products as the indicator of productivity. This combination 'defines the range of well organised farm N management'.

A very low NUE is undesirable as it indicates inefficient resource use and likely high environmental loss. However, a very high NUE could also be undesirable, indicating possible depletion of the resource pool (for example, soil N in the case of a farm or crop system, or body protein reserves in the case of an individual dairy cow). Whether this depletion of resources is a problem depends on time scale. For example, mobilisation of body protein reserves in early lactation is an adaptation to support lactation and not a problem, across the whole lactation, if those reserves are restored in later lactation.

The EUNEP report also recommends that, for arable farms, NUE should be calculated and expressed across the whole crop rotation. Shorter periods may be justified where crop rotations are short and stable. For animal production systems, calculation across the whole lifetime of an animal is recommended.

As discussed above, changes in pool size can distort NUE, giving misleading comparisons across time within farm, or between farms. At farm level, the N pool comprises of the N in soils, crops, livestock, stored feeds and stored manures, with soil N most likely to be the largest amount.

9.2.2 Nitrogen in soils

Soil contains between two and 10 tonnes of N per hectare. While a small proportion is in the form of ammonium and NO_3^- directly available to growing crops, most is stored in soil organic matter. Around 2% of organically-bound soil N is mineralised annually, and soil N will gradually deplete unless this is replaced (e.g. by crop roots and stubble, N fixation and animal manure). Soil organic N content is difficult to measure, as it varies spatially and is affected in the short term by events such as manure application, cultivation and weather conditions. EUNEP (2016) recommends measurement over a complete rotation (including the lifetime of temporary grasslands or 'leys').

9.2.3 Efficiency targets

In addition to NUE, EUNEP (2016) notably recommends that targets are set for the total N surplus which can be used as a 'rough guide' for N losses to the environment. The setting of, and adherence to, such a target, expressed at farm level as kg N/ha/year, can support compliance to specific local regulations on nitrate-N and help minimise the hard-to-measure emissions of NH_3 and N_2O. The report acknowledges that, as with the target NUE range and the target N output, the exact target values for N surplus will depend on farming system, region and soil type.

9.2.4. Effects of production intensity and fertiliser inputs

On livestock and mixed farms, stocking rate (livestock units/ha) is an important determinant of farm-level NUE and N surplus. Higher stocking rates may exceed the capacity of the farm to produce animal feed and utilise animal manures, thus increasing the rate of flow of N into the farm, in purchased feed and fertiliser, and increasing the risk of losing surplus N to the environment. However, such intensive farms (intensive in the sense of a high rate of production) could be components of efficient and productive farming systems if N surpluses can be successfully exported to, and utilised by, other farms, for example in the form of manures.

Inefficient use of N on farms arises partly from fundamental biological limits, but also reflects attitudes to risk and genuine waste.

Amounts of N applied to crops as fertiliser or offered to livestock in feed are generally the result of calculations to meet requirements for given levels of crop or animal performance, or to elicit desired responses in crop or animal performance.

Responses of crop yields to N fertiliser, and of animal performance to dietary protein, are curvilinear. The level of input that elicits the maximum performance response will be higher than that which elicits the maximum efficiency. It is common for farmers and their advisors to search for the point where the value of the response equals the cost of the input (e.g. unit of N fertiliser or increment in dietary protein). If the environmental costs of diminishing NUE are not taken into account, the economic optimum level of N input will be overestimated.

9.2.5 Managing risk and effects on efficiency

Models to calculate requirements and predict responses, and the data used to drive them, are subject to uncertainty, and they are often applied to aggregations of diverse sub-units (e.g. when the same diet is formulated for, and offered to, cows at different stages of lactation). Thus, it is common to use 'safety margins', oversupplying N when formulating diets or determining fertiliser application rates. Precision farming (applying management decisions to smaller sub-units within the farming system), using improved information (e.g. manure composition), improved decision support systems (e.g. ration formulation software) and improved physical equipment (e.g. 'low-emission flooring' in cattle barns, keeping urine and faeces separate) should reduce the value of, and justification for, safety margins, therefore incrementally and progressively improving NUE.

9.2.6 Example farm level models to calculate NUE

Several models have been developed which quantify farm level NUE for dairy farms, including the Integrated Farm Systems Model (IFSM) developed in Wisconsin[9] and the Annual Nutrient Cycling Assessment (ANCA) tool developed in the Netherlands. These models have been used in research studies to explore the magnitude of effects of management changes. For example, use of the IFSM to simulate different dairy farm typologies and farming practices in the US has highlighted opportunities to improve farm level NUE thereby reducing NH_3 and N_2O emissions by 15% and 43% respectively[10]. This is achieved through reducing applications of fertiliser N to maize, and by reducing dietary CP concentration while maintaining supply of essential amino acids in relation to dietary energy in cow rations.

Such models can also be used for calculating 'nitrogen footprints' of real farms. In the Netherlands, use of the ANCA model ('Kringloopwijzer', in Dutch) to calculate annual balances of N and phosphorus is obligatory for dairy farmers through contracts with milk buyers. Development and use of this system is a collaboration between trade organisations representing farmers, milk processors and feed suppliers, with further technical development by Wageningen University Research funded by the Dutch Ministry of Agriculture, Nutrition and Food Quality. Relevant indicators for N efficiency are NUE (N output/N input, at farm, crop, and herd level), N surplus (kg/ha = N input – N output, at soil and farm level), N excretion (urine plus faeces, kg/ha) and specific losses of N as NH_3 (kg/ha), NO_3^- (mg/l groundwater) and N_2O (kg CO_2-eq/ha). This is consistent with the approach advocated by EUNEP (2016). Carbon auditing tools allow farmers to quantify their emissions across a whole farm and per enterprise, but the focus on CO_2 equivalents means that the only N-compound routinely accounted for is N_2O. Most carbon auditing tools provide a breakdown of emissions from CO_2, CH_4, and N_2O from all farm enterprises whether it be dairy, beef, sheep, pig, poultry or arable.

Carbon auditing tools allow farmers to quantify their emissions across a whole farm and per enterprise. The focus on CO_2 equivalents means that the only N-compound routinely accounted for is N_2O.

9.3 Animal and herd or flock level

9.3.1 Lactating cows

NUE in lactating dairy cows is calculated as milk N yield divided by N intake (where milk N = milk CP/6.38 and N intake = CP intake/6.25). This metric is readily calculable for both the herd and individual lactating cows. Three of the four parameters needed for this calculation (milk yield, milk N content and diet N content) are available through routine milk recording schemes and diet formulation and analysis. The fourth, dry matter intake, can be back calculated from cow performance and diet composition, or predicted from animal and diet characteristics using one of numerous published models.

Like feed conversion efficiency (daily milk yield of standardised composition/feed dry matter intake), NUE in lactating cows will vary with the contribution from or to body protein (i.e. changes to size of the body N pool). For example, the NUE metric will be elevated in very early lactation, when some of the amino acids incorporated into milk protein originate from mobilised body protein. It has been estimated that, in the second week of lactation, body N loss accounted for 29% of milk N output[11] (so that NUE was 44% in weeks one to five of lactation, dropping to 38% in weeks six to 10). Furthermore, there is evidence that 'metabolic N efficiency' (= milk output + body N change/N intake) declines slightly as lactation progresses (from 66% to 62%). Consequently, comparisons of animal level NUE between farms or within farms across time should be made at the same stage of lactation.

While NUE of the lactating cow is the major driver of herd NUE, it fails to account for N use by replacement calves and heifers, or the effects of disease, fertility and herd management decisions (e.g. length of lactation) on the proportion of non-lactating animals in the herd. Lifetime NUE is highly correlated with NUE during lactation (r=0.97) but is also affected by calving interval (a measure of fertility) and age at first calving. In short, minimising the number of non-productive days in a dairy herd will improve both NUE and GHG emission intensity for both herd and farm.

Milk urea (often reported as milk urea nitrogen, or MUN) is widely available to dairy farmers, advisors and researchers through regular milk testing, with a variety of advisory guidelines available to aid interpretation. MUN is closely and directly related to concentration of urea in blood and is a good predictor of dairy cow NUE in most practical feeding situations (below about 20% CP in dry matter). While MUN will be influenced by the balance between rumen degradable N and fermentable organic matter, and by the profile of amino acids in metabolisable protein, the main factor explaining variation in MUN is N intake.

9.3.2 Growing animals

Calculation of animal level NUE is more difficult in growing animals than lactating cows as body protein gain is known with less certainty than secretion of milk protein. NUE can be calculated where growing animals are regularly weighed, making assumptions for the N content of body weight gain. Accuracy will be affected by how alike growing animals are in terms of genetics, age, feeding history, health history and whether they shared a common environment. Where individual animals differ in some of these regards, there can still be value in measuring efficiency at the level of management groups.

9.3.3 Research settings

The alternative to measurement of NUE is measurement of N use inefficiency, which requires direct measurement of N excretion. For individual animals, this is only possible in a research setting. Since the chemical form and potential environmental impact of excreted N differs between faeces and urine, separate knowledge of faecal N excretion and urinary N excretion could inform management decisions.

Taking dairy cows as the example, efforts have been made to predict faecal and urinary N excretion from information that may be available to farmers and advisors. Models including N intake performed better than models based on dietary composition alone. For both faecal N and urinary N output, models driven by milk outputs (milk yield, protein content and urea content) performed similarly to models driven by diet composition (dietary CP and NDF concentrations).

9.4 Managing nitrogen resources

Farm inefficiency of N use arises partly from fundamental biological limits, but also reflects attitudes to risk, genuine waste and economic returns. For example, use of 'safety margins' as an insurance policy when formulating diets or determining fertiliser application rates is common practice i.e. overfeeding of one or more nutrients to ensure there is low risk of them being deficient. Improved information and improved decision support systems should be used to identify where major N imbalances are in the system and reduce the value of, and justification for, oversupply of N above requirements or capacity. The aim should be to minimise these losses through an understanding of the factors that influence N losses, animal and plant productivity, and need for N inputs.

Nitrogen is such an important nutrient for natural biological cycles, with great impact on plant and animal production, that calculation of herd or flock level NUE should be a component of normal farm management practice, regardless of the model chosen.

Nitrogen is such an important nutrient for natural biological cycles, with great impact on plant and animal production, that calculation of herd or flock level NUE should be a component of normal farm management practice, regardless of the model chosen.

10. CIEL commentary

By Katerina Karpasitou and Dr Mark Young, CIEL

Agriculture has been an integral part of the heritage of world cultures and communities through providing sustenance, economic prosperity and a cultural identity deeply rooted in the countryside. Against this backdrop, N cycling is a topic of fundamental importance, particularly in the context of livestock farming.

Nitrogen, an essential element for all living organisms, plays a pivotal role in sustaining healthy ecosystems, both natural and agricultural. Livestock farming relies heavily on N inputs, primarily as fertilisers and animal feeds, to promote high productivity of feed crops and livestock. Nitrogen is also a unique element in nutrition being associated with protein but not carbohydrates or lipids. However, sub-optimal management of N can lead to pollution and environmental degradation, negatively impacting ecosystems and human health, and contributing to climate change. We are becoming more aware of these negative impacts but need to look at them in the context of how N moves through the food system and also account for the value it adds.

To address the challenges, a multifaceted approach is required, involving various stakeholders: government, policymakers and regulators; scientists, research institutions and innovators; fertiliser producers, animal feed manufacturers, farmers and, ultimately, consumers. Collaboration is needed to ensure our food systems make best use of resources but do not waste them. To raise awareness, support research and development of innovative solutions, and to implement best practice, we must have a holistic understanding of the food system. The N cycle underpinning the food system is a key concept to understand.

This report outlines the important role N has in promoting crop growth and animal performance, together with the importance it has in transforming lower-quality feed components into high-quality protein. Livestock hold a unique position in this process through their ability to transform lower-quality feeds into very high-quality food products. Ruminants are uniquely capable of being able to harness the power of their rumen microbiome to 'add' protein to the equation while also breaking down complex carbohydrates (fibre) that cannot be digested by most other animal species. The N cycle is fundamental to this special process.

So how can we improve the efficiency with which we use nitrogen, and avoid excessive losses from the food system?

- Innovative feed options can be used to maximise the efficiency with which animals use protein which will reduce N content in animal waste and so play a significant role in increasing NUE within livestock systems
- Adoption of technological solutions to hold or capture more N will be key strategies to improve efficiency in food production while minimising and capturing losses from the N cycle
- Smart farming systems using sensor networks can help farmers manage N inputs through monitoring soil health, meeting crop N requirements and managing livestock manure appropriately. Data is key to delivering in this area
- Artificial intelligence can use rich datasets to aid in predicting N demand and potential for losses across landscapes, allowing optimisation of fertiliser and manure applications, to maximise NUE
- Embracing circular economy principles through integration of livestock farming with crop production can help close nutrient loops for N and other key nutrients, reducing need for synthetic inputs, simultaneously increasing nutrient use efficiency and reducing carbon footprint

Several areas require innovations to enhance our ability to better manage N resources. These include:

- Cheap and accurate methods for measuring N in the soil pool, by far the largest pool of N on most farms. This is critically important in modelling the N cycle since, as the largest pool, it acts as a buffer for plant production from a series of N inputs, including the capture of N from animal dung and urine
- Robust and easy-to-use information systems for managing N resources that account for changes over relevant timescales and differential distribution of N in landscapes, to reduce need for additional inputs as safety margins for achieving performance goals:
  - For soils to help manage spatial application of organic and inorganic fertilisers
  - For body protein changes in lactating and growing animals at level of management groups or at individual animal level where nutritional control can be applied at that level
- Simple, intuitive systems that allow us to equate different N pools or flows on a common scale of impact i.e. equating nutritional value of protein quality, to N value as a fertiliser, to pollution impacts of N_2O (atmosphere) and NO_3^- (water ways). This will help optimise N use models

Livestock are a key element of our food system for good reasons. They upcycle nutritional quality of feed to produce highly nutritious food and they play an important role in returning nutrients to soils through manures. This dual role is a key pillar for 'regenerative agriculture'.

This report shows where N can enter or leave the food system. Our aim should be to minimise unnecessary loss, through an understanding of the natural cycle and the use of innovative technologies to capture nutrients at risk of loss, together with monitoring N pools and flows between them on farm, to actively manage N resources.

It is not a question of whether we need livestock. Rather it is how should we make best use of livestock. So, while livestock farming is increasingly subject to scrutiny in terms of its environmental impact, we must also shift perspective and recognise the potential of livestock farming as a catalyst or opportunity for promoting better environmental stewardship and sustainable agricultural practices. This will strengthen the resilience of the agricultural sector in the face of climate change and uncertainty, while continuing to play a vital role in providing society with essential nutrients in a highly-nutritious form.

CIEL commends this report to the agri-food sector, government and wider public interested in farming and food, both here in the UK and abroad, to help inform debate about sustainable food systems.

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Authors

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12. Glossary

Amino acid	Building blocks of protein
Cellulolytic microorganisms	Bacteria able to break down cellulose from plant cell walls by secreting enzymes
Deaminated	Removal of amines (NH_2 groups) from proteins
Essential amino acid	Amino acids which cannot be synthesised by an animal and must be supplied through the diet
MUN (Milk Urea Nitrogen)	Indicator of protein and energy balance status in cattle
NDF (Neutral Detergent Fibre)	A laboratory method for measuring indigestible fibre in a feed (component). Ruminants benefit from microbes digesting fibre in rumen, something that humans and many other animals cannot do. This is used by the feed industry as a measure of how fibrous (lower-quality) a feed (component) is
NUE (Nitrogen Use Efficiency)	Defined in section 5.7
Peptide	Short chain of amino acids
Protected protein or Protected amino acid	Rumen protected protein/amino acids in a feed have been treated or processed in a way to reduce degradability in the rumen so that they pass through to the lower gut unchanged for digestion and absorption by the ruminant animal itself
Symbiotic	A relationship between different organisms that both benefit from
VFA (Volatile Fatty Acids)	Produced during microbial fermentation in the rumen and absorbed there, these are the main energy source for a ruminant animal
Nitrogen - chemical compounds relevant in this report	
N (Nitrogen)	The symbol for one atom of elemental nitrogen. Nitrogen does not exist freely in this form
N_2 (Nitrogen gas)	The dominant gas in the Earth's atmosphere and the form captured by nitrogen-fixing bacteria in the environment
NH_3 (Ammonia)	A common air pollutant arising from manures and other biological material breaking down. At high concentrations it is an irritant to breathing and regulations limit the levels that animals and humans should be exposed to
NH_4^+ (Ammonium)	An ion that is part of some salts. Ammonium nitrate is a potent nitrogen fertiliser used to stimulate plant growth and increase crop yields
N_2O (Nitrous oxide)	A potent greenhouse gas that has 273 times the warming potential of CO_2
NO (Nitric oxide)	This is not a greenhouse gas but is a serious pollutant generated by automotive engines and thermal power plants
NO_3^- (Nitrate)	An ion that is part of some salts. Ammonium nitrate is a potent nitrogen fertiliser used to stimulate plant growth and crop yields
NO_2^- (Nitrite)	An ion that is part of some salts. Nitrites can be used as food preservatives

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