

From the animal to the region, a critical look at nitrogen use efficiency of dairy cattle systems

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■ Nitrogen-use efficiency and the nitrogen balance are common indicators used to assess production systems and their environmental impacts. Many mechanisms exist to improve them. However, does the overall improvement at the system level result from improvements in each of its components? Does an increase in efficiency always lead to a decrease in losses?

Introduction

Nitrogen (N) is an element essential for life on Earth and one of the main factors that limits agricultural production. The main sources of N in agricultural systems (i.e. symbiotic fixation by legumes, organic N inputs and industrial synthesis of ammonia (NH₃) for mineral fertilisers) have enabled a rapid increase in agricultural production to meet the food demand of the growing world population (Erismann *et al.*, 2008). However, N-use efficiency (NUE) (i.e. the N output obtained per unit of N used) is moderate to low, at ca. 50% globally and 36% in Europe (Sutton *et al.*, 2011). As a result, N losses from human activities, especially agriculture, have become a global environmental threat. The volatilisation and deposition of this N in the form of NH₃ or nitrous oxide (N₂O, a greenhouse gas) resulting from nitrification-denitrification processes and nitrate leaching has several impacts: eutrophication, acidification of environments, loss of biodiversity at

the local scale, public health at the regional scale and climate change at the global scale (Steffen *et al.*, 2015; Campbell *et al.*, 2017). In this context, the “N challenge” requires drastically reducing N losses while continuing to increase global food production. Among the options identified, improving the efficiency of N use in agriculture has the most potential (Bodirsky *et al.*, 2014).

Livestock production consumes large amounts of N, mainly in forage, grain and oilcakes. Ruminants can convert N from forage that cannot be consumed by humans into high-quality protein-rich animal products, making these products an essential link in the nutrient cycle. However, this conversion is not complete and results in N losses at multiple levels, from the animal to the agricultural region. NUE and the N balance are the two main types of indicators used in research or for advice to characterise N use. NUE is the ability of the system (e.g. animal, farm) to convert N inputs into outputs. It reflects the percentage of N inputs

that is converted into products. The N balance, which is the amount of unused N, increases as N inputs increase, due to a NUE less than 100%. One challenge of estimating the NUE and N balance of livestock systems is the wide variety of indicators available (Table 1). These indicators differ in their objectives and in the level considered (e.g. animal, herd, farm, region). Calculation of the indicators can also differ among studies and depend upon the data available; for example, some studies do not consider atmospheric deposition, while others consider changes in soil N (Godinot *et al.*, 2014).

Many studies at the animal or farm level aim to identify practices that improve the NUE of livestock production. While these practices are often associated with a decrease in the N balance, and thus N losses to the environment, their impacts at larger scales are rarely addressed.

The first section of this synthesis illustrates the main mechanisms that improve NUE and can reduce N losses

Table 1. Indicators of nitrogen-use efficiency (NUE) and the nitrogen (N) balance commonly used for dairy systems, as well as their calculation methods and mean value ranges in France according to the literature.

Scale	Name	Acronym ^(a)	Calculation ^(b)	Range	Source
Nitrogen-use efficiency					
Animal	PDI efficiency 2007 ^(c)	EffPDI 07	$MPY^{(d)} / (PDI_{intake} - PDI_{requirements})$	60-70%	INRA (2007)
	PDI efficiency 2018	EffPDI 18	$Protein\ expenditures^{(e)} / (PDI_{intake} - PDI_{req_EUP}^{(f)})$	50-80%	INRA (2018)
	Feed N-use efficiency	FNUE	$N_{animal\ products}^{(g)} / N_{intake}$	0-35% ^(h)	Van der Hoek (1998); Peyraud <i>et al.</i> (2012a)
	Milk N efficiency	MNE	N_{milk} / N_{intake}	20-35%	Castillo <i>et al.</i> (2000); Peyraud <i>et al.</i> (2012a)
Field, farm, region	Soil N efficiency	SNUE	$Plant\ N_{outputs} / N_{supplied\ to\ the\ soil}$	30-90%	Leip <i>et al.</i> (2011)
	Nitrogen-use efficiency	NUE	$N_{animal\ and\ plant\ outputs} / N_{inputs}$	15-40%	Aarts <i>et al.</i> (2000)
Nitrogen balance					
Animal	Nitrogen excreted	N excreted	$N_{intake} - N_{animal\ products}^{(g)}$	330-600 g N/d/cow	Peyraud <i>et al.</i> (2012a)
Field, farm, region	Soil Nitrogen balance	Soil N balance	$(N_{supplied\ to\ the\ soil} - plant\ N_{outputs}) / UAA^{(i)}$	- 35 to 65 kg N/ha	Foray <i>et al.</i> (2017)
	Nitrogen balance	N balance	$(N_{inputs}^{(j)} - N_{outputs}) / UAA$	10-500 kg N/ha	Simon and Le Corre, (1992); Foray <i>et al.</i> (2017); European Environment Agency (2019)

^(a)Commonly found in the literature.^(b)Variables expressed in units of mass per unit time (e.g. g N/d, kg N/d, t N/year).^(c)Calculated from protein fractions in g/d; PDI = Truly digestible (dietary + microbial) protein (INRA, 2007).^(d)Milk protein yield.^(e)Includes all protein produced and exported by the animal (i.e. milk protein, non-productive protein such as endogenous faecal protein, protein exported in the scurf and protein accumulated during growth or late gestation) (INRA, 2018).^(f)PDI requirement associated with endogenous urinary protein (INRA, 2018).^(g)N from milk and meat.^(h)All cattle systems.⁽ⁱ⁾N inputs include mineral fertilisers, manure (spread or deposited during grazing) and imports of organic waste. Outputs include the N exported in plants by harvest or grazing. UAA: Utilised agricultural area.^(j)The N balance may or may not include symbiotic N fixation by legumes and/or atmospheric deposition. In this article, these sources are included in the N inputs.

at different scales (e.g. animal, farm, region). The second section discusses consequences of upscaling to assess whether the overall increase in system efficiency equals the sum of its parts (i.e. the increase in efficiency of each component of the system). The third section analyses whether an increase in efficiency is always associated with a decrease in N losses. Finally, the fourth section explores the relevance and limitations of these indicators for dairy cattle systems.

1. Main mechanisms for improving nitrogen-use efficiency at different levels

Regardless of the level of organisation, the N not used to produce plants or animals will be emitted into the environment and can contribute to air and water pollution (e.g. NH₃ volatilisation, N₂O emissions from soils, nitrate leaching). This loss of N is also expensive

for farmers and a source of economic inefficiency, which justifies identifying mechanisms that optimise N use at each level of the system.

■ 1.1. Animal level

At the animal level, NUE and protein-use efficiency are indicators calculated to assess N use. NUE is defined as the ratio of the amount of N exported (in milk and/or meat) to the amount of N ingested (e.g. feed NUE (FNUE) or

milk NUE (MNE); Table 1). Protein-use efficiency is defined as the ratio of the amount of protein exported by an animal (in milk, meat and/or non-productive protein fractions) to the total amount of protein that is absorbed during digestion (EffPDI; PDI is truly digestible (dietary + microbial) protein, the equivalent in INRA (2018) system to Metabolisable Protein; Table 1). Nitrogen-use inefficiency ($1 - \text{FNUE}$ or $1 - \text{MNE}$) results in N excretion in urine and faeces, while protein-use inefficiency ($1 - \text{EffPDI}$) results in N excretion in urine due to catabolism of protein amino acids (AA).

Faecal N excretion (150-200 g N/cow/d for a cow ingesting ca. 600 g N/d) is caused by non-digestible dietary N, undigested microbial N and an endogenous fraction of N. It depends mainly on the total amount of dry matter ingested (8.42 ± 2.02 g faecal N/kg dry matter ingested; INRA, 2018) and little on the N content of the diet. Faecal N is excreted mainly in organic forms, which are unlikely to volatilise into NH_3 (Peyraud *et al.*, 1995). Urinary N excretion varies

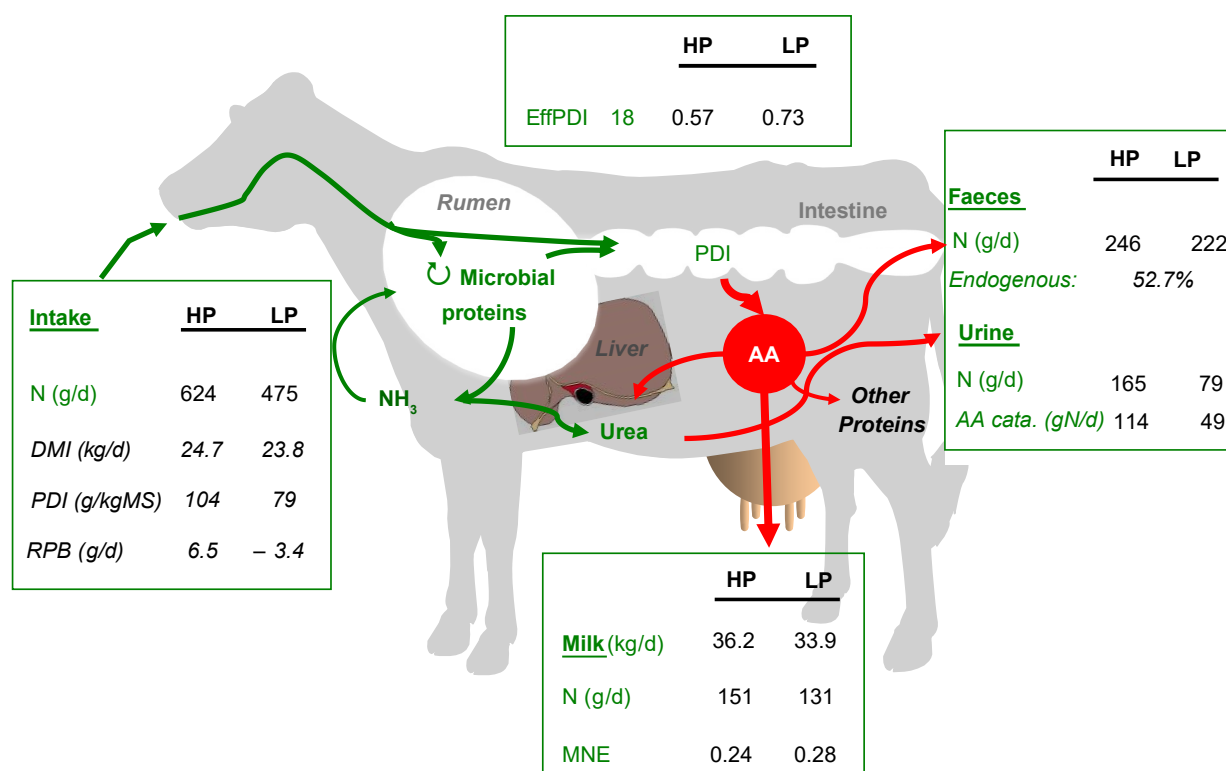
greatly and depends greatly on the crude protein (CP) content of the diet (e.g. decreasing by 66% when the CP content of the diet decreased from 20% to 15%; Castillo *et al.*, 2000). Urinary N comes mainly from urea (50-90%; Bussink and Oenema, 1998), which is the main source of NH_3 volatilisation in ruminant manure.

Many studies have shown that each 10 g/kg decrease in CP in the diet results in a net increase of 1.2-1.4 percentage points in MNE (Huhtanen and Hristov, 2009). The type of N supplied in the diet can also be modified, beginning with the proportion of rumen-degradable protein. The aim is to improve the balance between soluble N and fermentable organic matter, because having more degradable protein than fermentable energy in the rumen significantly increases excretion of urea in the urine (Vérité and Delaby, 2000). In the INRA (2018) feeding system, this balance is estimated as the rumen protein balance (RPB) (i.e. CP intake minus non- NH_3 CP entering in the duodenum). Thus, diets with a negative RPB

(12% CP, RPB = ca. -10 g/kg DM) have a NUE that is 10 percentage points better (MNE = 31%) than those of diets with a positive RPB (18% CP, RPB = 24 g/kg DM, MNE = 20%; Edouard *et al.*, 2016, 2019). Diets that are deficient in rumen-degradable protein promote the reuse of urea for microbial synthesis.

The second source of urinary N production is the catabolism of protein AAs into urea. PDIs are hydrolysed into AAs during intestinal digestion, and each tissue or organ takes these AAs up to synthesise proteins. Even in diets with a limiting proportion of degradable protein, hepatic catabolism of AAs and its contribution to urinary N is not negligible (Raggio *et al.*, 2004). The INRA (2018) ruminant feeding system calculates PDI-use inefficiency ($1 - \text{EffPDI}$ 18, Table 1) to estimate AA catabolism. Thus, a 24% decrease in N intake in the diet, which is a large decrease in the diet's PDI content (from 104 to 79 g/kg DM), increases MNE by 4 percentage points and EffPDI 18 by 16 percentage points (Figure 1). These increases are

Figure 1. Nitrogen (N) flows (in milk, faeces and urine) and use efficiencies for dairy cows fed a high-protein (HP) or low-protein (LP) diet (data from Raggio *et al.* 2004).



Inputs and efficiency of PDI (truly digestible protein; INRA, 2007) were recalculated according to INRA (2018). The indicator EffPDI 18 was used to estimate the percentage of urinary N from amino-acid (AA) catabolism (AA cata), the percentage of faecal N from faecal endogenous protein (endogenous) and the rumen protein balance (RPB). A positive RPB indicates excess ammonia (NH_3) in the rumen, while a negative RPB indicates N recycled as urea in the rumen. DMI: dry matter intake, DM: dry matter, MNE: milk N-use efficiency.

due mainly to a decrease in the catabolism of AAs into urea (52%) and by an increase in urea recycled in the rumen. This decreases excretion of urinary N greatly (57%) and that of faecal N to a lesser extent (– 10%).

Reducing PDI supplies thus increases their efficiencies (EffPDI 07 and EffPDI 18) of utilization. Reducing PDI supplies decreases the supplies of all AAs (essential and non-essential) leading to a decrease in the catabolism of many AAs that are supplied in excess (Haque *et al.*, 2015). However, it can also decrease milk and milk-protein yields (– 6% and 12.5%, respectively; Figure 1). Nevertheless, the decrease in milk-protein yield is smaller than that in PDI intake. Better balancing the AA profile (i.e. LysDI, MetDI and HisDI for Lys, Met and His Digestible in the Intestine) can partly limit the decrease in milk-protein yield and thus increase PDI-use efficiency (Broderick *et al.*, 2009; Haque *et al.*, 2012, 2015; Lemosquet *et al.*, 2014). Better balancing LysDI and MetDI supplies in mid-lactation cows increases by 2-3 and 2-5 percentage points the N-use and PDI-use efficiencies, respectively (Haque *et al.*, 2012, 2015; INRA, 2018). These efficiency gains are lower, however, than the increase

obtained (10 percentage points) when decreasing PDI intake from 100 to 90 g/kg DM (Lemosquet *et al.*, 2014; INRA, 2018). Dietary factors other than N intake, such as increasing energy supplies and providing a high-starch diet, can also increase protein-use efficiency by increasing milk-protein yield (Rigout *et al.*, 2003; Brun-Lafleur *et al.*, 2010; Cantalapiedra-Hijar *et al.*, 2015).

■ 1.2. Farm level

At the farm scale, NUE is the indicator used most often (Powell *et al.*, 2010; Leip *et al.*, 2011; Quemada *et al.*, 2020) (Table 1). It is calculated as the ratio of the N in agricultural products leaving the farm (e.g. milk, meat, crops) to the N in inputs (e.g. feed and seeds, organic and mineral fertilisers, symbiotic fixation by legumes, purchase of replacement animals, atmospheric deposition). This indicator usually accompanies the N balance, which is calculated as the difference between the same variables (inputs – outputs), and represents the “pollution potential” of the farm (Simon and Le Corre, 1992; Table 1). The N balance is commonly used to assess the overall N management of farms and the pressure they exert on the environment.

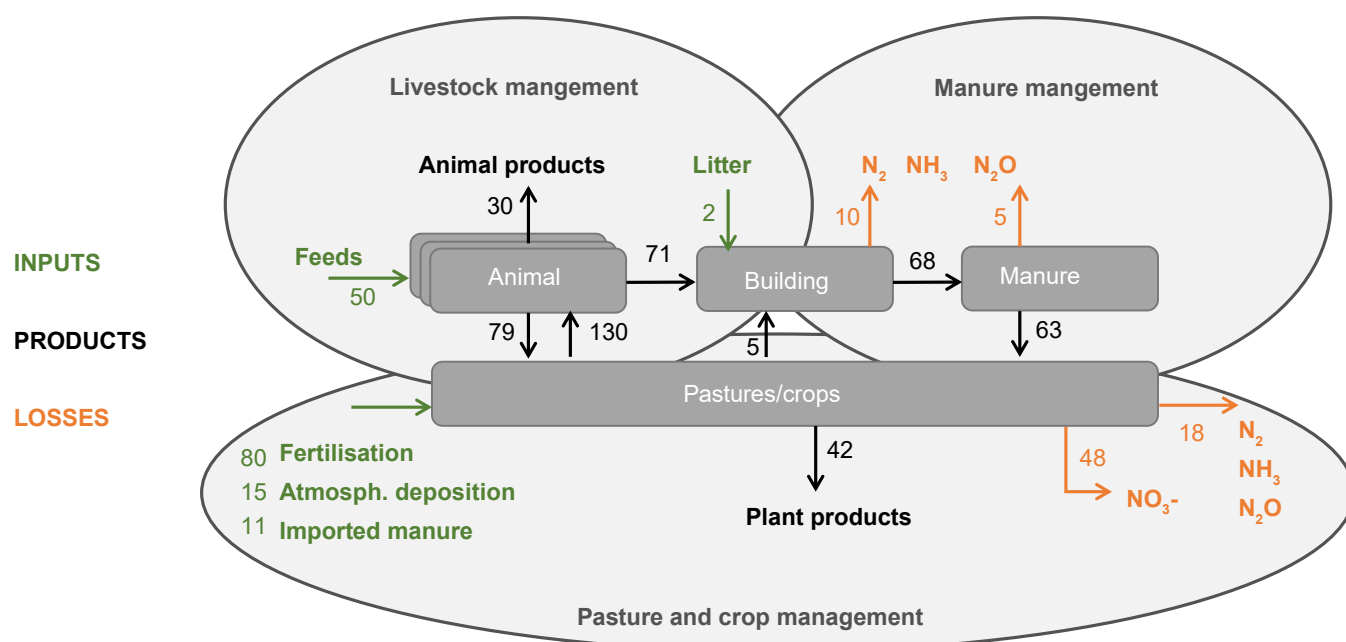
The mechanisms implemented to improve NUE include herd management (e.g. breed, feed, reproduction and renewal), manure management, plant management and N recycling on the farm (Figure 2).

a. Herd and manure management

Increases in efficiency related to animal genetics or breed are difficult to quantify because these mechanisms are usually associated with a given breeding system. A simulation study, based on results of the “Which cow for which system?” experiment conducted at the INRAE experimental farm of Le Pin-au-Haras, was conducted to assess the influence of animal-, feed- and herd-management factors (Box 1). Its results highlight the utility of an overall and integrated approach for assessing the factors involved in the management, efficiency and fate of N and, more generally, the environmental performance of dairy systems.

Combining complementary forages to a herd's diet improves NUE due to their differing N and energy balances. For example, a diet with 80% maize silage and 20% lucerne increased the MNE by 6.5 percentage points and reduced urinary N excretion by nearly

Figure 2. Nitrogen (N) flows (kg N/ha utilised agricultural area (UAA)/year) on a dairy farm in Brittany, France, with 80 ha of UAA, including 25 ha of cereals, and 82 livestock units (adapted from Peyraud *et al.* 2012a).

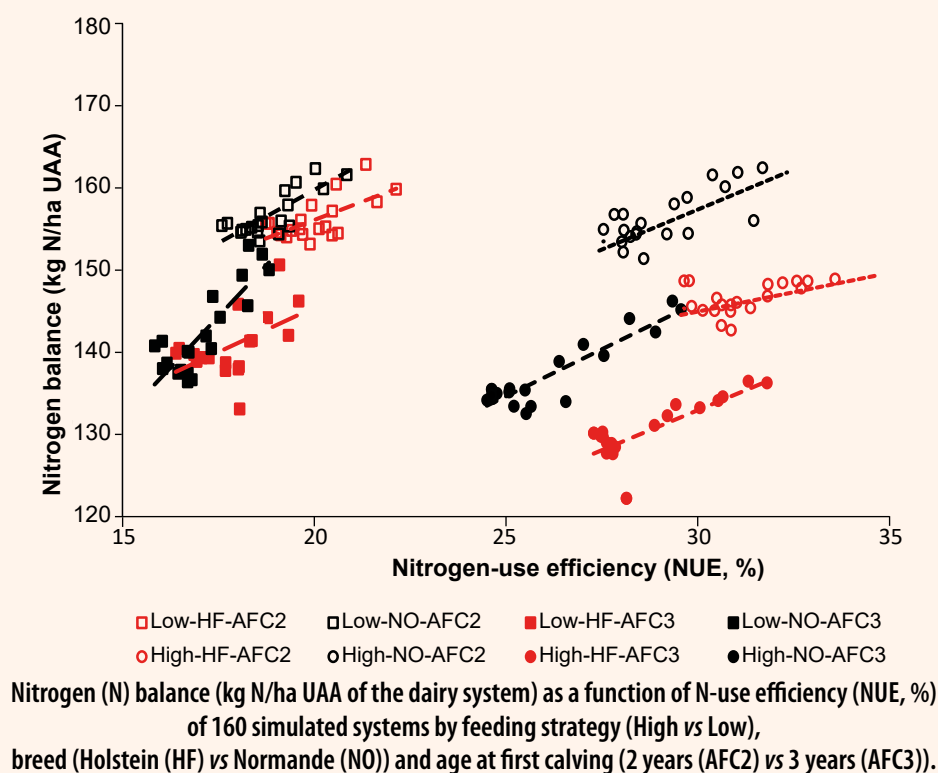


Box 1. Simulations of nitrogen-use efficiency and the nitrogen balance for a variety of dairy systems based on data from the “Which cow for which system?” experiment (Foray et al., 2020).

The “Which cow for which system?” experiment, conducted for 14 years at the INRAE experimental farm of Le Pin-au-Haras (France, DOI: 10.15454/1.5483257052131956E12), was used to estimate the influence of *i)* the breed (Holstein or Normande), *ii)* the genetic type (higher potential for milk production at the expense of lower milk fat and protein concentrations, or vice-versa), *iii)* the age at first calving (2 or 3 years), *iv)* the feeding strategy (high or low, corresponding to the presence or absence, respectively, of concentrates and maize silage in the diet), *v)* the strategy for selling heifers in excess of renewal (at 15 days of age or when they are still pregnant) and *vi)* the renewal rate of the herd (20%, 25%, 30%, 35% or 40%) on nitrogen (N) flows and losses (Foray et al., 2020).

By combining the 160 treatments tested ($2 \times 2 \times 2 \times 2 \times 2 \times 5$), the data collected in the experiment were used to simulate 160 dairy systems that had the target of producing 400 000 L of fat-and-protein-corrected milk per year. The herd demographics of each system simulated were defined from the experimental data to meet the production target. The area dedicated to each herd was determined from the amount of forage required per feeding period, and thus differed among systems. Multi-criteria environmental analysis of each system was performed using the CAP’2ER tool (<https://cap2er.eu/>) to estimate, among other things, N-use efficiency (NUE) and the N balance.

For all simulations, at the scale of the dairy system, the NUE was $24 \pm 5\%$, and the N balance was 146 ± 10 kg N/ha utilised agricultural area (UAA). The most efficient system (NUE = 33.6%) was the Holstein system with a milk fat and protein concentrations-oriented strategy, an age at first calving of 2 years, a high level of feeding, heifers sold at 15 days and a renewal rate of 20%. Its N balance was, however, above the mean, at 149 kg N/ha. The low feeding level had a significantly lower NUE than the high feeding level did (18.5% vs 28.8%, respectively); however, despite having a significantly larger N balance (149 vs 143 kg N/ha UAA), it had less potential for N leaching (46 vs 69 kg N/ha UAA, respectively) due to more N immobilisation (57 vs 22 kg N/ha UAA, respectively) caused by a larger grassland area. Similarly, for a given breed and feeding strategy, a decrease in the renewal rate improved NUE but increased the N balance (see graph), as this system required less area (especially grassland) to rear heifers.



This study, which also calculated other environmental indicators (especially greenhouse gas (GHG) emissions; Foray et al., 2020), highlights the challenges in establishing a reference system that would identify the most relevant efficiency and environmental indicators, especially due to certain antagonisms. For example, the system with the lowest GHG emissions per L of milk (1.03 kg CO₂-eq./L) had one of the highest N balances (160 kg N/ha), whereas the system with the lowest N balance (122 kg N/ha) would have emitted more GHGs for the same amount of milk produced (1.15 kg CO₂-eq./L milk).

20% compared to a diet with the opposite percentages (20% and 80%, respectively; Arndt et al., 2015) due to the 1.5 percentage-point decrease in the N content of the diet. At the farm level, however, it is important to consider not

only the feed-use efficiency of the animals, but also the N flows within the farming system. While dairy systems based on a large percentage of conserved forage in the herd's diet (maize silage > 30% of the forage area (FA)) generally

have better feed-use efficiency than grass-based systems do, NH₃ emissions at the farm level are often higher (e.g. a 4 percentage-point increase in efficiency, but a 30% increase in N-NH₃ emissions per t milk in western France;

Faverdin and van Milgen, 2019). This increase is associated with the animals spending more time in the building and more manure stored, which increases gas emissions, and with intensification of milk production per ha due to large amounts of purchased supplemental protein. This intensification leads to higher N inputs per ha and thus an increase in N losses.

At pasture, N concentrate supplies have little influence on milk production based on well-fertilised grasslands in the spring (60 kg N/ha), suggesting that a sufficient amount of grass can provide the energy and protein required to produce 25-27 kg milk/cow/d (Delaby *et al.*, 1996). Moderately fertilising grasslands rather than supplementing protein for the animals can increase grassland productivity and thus increase the number of grazing days per ha (312 grazing days/ha with grasslands fertilised at 60 kg N/ha/cycle vs 206 grazing days/ha with grasslands fertilised at 20 kg N/ha/cycle in the spring; Delaby *et al.*, 1996). This double effect of N fertilisation in spring improves system efficiency more than supplying protein-rich concentrates.

Feeding strategies (whether including grazing or not) and diet characteristics (e.g. type of forage, N content, N/energy balance) also influence the amount and composition of animal waste (e.g. faeces/urine partitioning, urea N content) in interaction with their management. When animals graze, their urine and faeces are deposited directly and separately, usually on active plant cover, which uses N directly. Urine diffuses rapidly in the soil pore space, far beyond its immediate impact zone. Because the soil can assimilate much of this N in organic form, volatilisation is low despite the large amounts of N that the animals deposit locally. Leaching losses are a more serious risk (Peyraud *et al.*, 2012b), although they can be limited if the instantaneous stocking rate is adapted to the amount of grass available. In buildings, N losses depend on the type and management of the manure. For diets that are excessively high in N (18% MAT; Edouard *et al.*, 2019), N-NH₃ emissions are higher when animals produce manure on deep litter (nearly 100 g N-NH₃/cow/d) than

when they produce slurry in open barns (68 g N-NH₃/cow/d). The high gas emissions (NH₃ and N₂O) during the management of manure from high-N diets (i.e. buildings to storage) result in a lower fertiliser value (total N and N-NH₃ content) than that of manure from lower-N diets (Edouard *et al.*, 2015), which may degrade the overall efficiency of the system.

Practices that reduce N losses along the building-storage-spreading continuum (e.g. slurry treatment, pit covers) are effective at reducing NH₃ and/or N₂O emissions and are thus essential to optimise efficiency at the farm level. However, these practices can have contrasting effects depending on the gas considered (including CH₄ and CO₂) or the season (Kupper *et al.*, 2020), which calls for assessing overall effects of these practices.

b. Crop management and fertilisation

At the crop level, breeding varieties with root characteristics that can access soil resources better, remobilise N better and have a higher harvest index has great potential to improve the efficiency of cropping systems (Hawkesford and Griffiths, 2019). Reducing crop fertilisation also improves NUE (Mueller *et al.*, 2017) according to Mitscherlich (1924) law of diminishing returns. This is especially true as the calculation of NUE does not generally consider changes in soil organic matter content (Godinot *et al.*, 2014). High mineralisation of soil organic matter, if not compensated for in the same year by applying an equivalent amount of organic matter, thus improves the efficiency of the system by emitting nitrogen, which can result in an efficiency greater than 100% in low-input cropping systems. This is a paradoxical situation in the long term as the efficiency improves at the expense of soil fertility (Quemada *et al.*, 2020). However, in some western European countries (e.g. France, Greece, the Netherlands), decreasing fertiliser inputs in the past few decades has not decreased crop yields, but instead has decreased N losses by 50 to 200 kgN/ha (Lassaletta *et al.*, 2014). This increase in efficiency is due to a decrease in waste associated with over-fertilisation (Mueller *et al.*, 2014).

Implementing all good fertilisation practices simultaneously ("right rate, right time, right place") can improve fertiliser-use efficiency (Li *et al.*, 2019). Fertilisers with better efficiency (e.g. with polymer coating or nitrification or urease inhibitors) can also improve crop NUE, but only when other good practices are also implemented (Li *et al.*, 2018). While mineral fertilisers generally have better NUE than organic fertilisers at the field and cropping-year scale (the ammonium-nitrate-equivalent coefficient of organic fertilisers ranges from 0.1-0.7 depending on the type of fertiliser and when it is applied), the results differ at the scale of a mixed crop-livestock farm and over the longer term. Livestock manure is a nutrient-rich co-product that can be used on the farm, exported to a neighbouring farm or, if too much is produced, treated to reduce its N content. Good agronomic use of waste can have a positive effect at the farm scale by decreasing the losses related to storing and spreading it, but also by decreasing the use of mineral fertilisers and the losses related to their manufacture and use. In addition to its value as fertiliser that supplies N, phosphorus and potassium, it is important to consider the influence of livestock manure on the organic matter content and physical, chemical and biological fertility of soil. Long-term experiments have shown that inputs of livestock manure can, in certain situations, have better NUE than equivalent inputs of mineral fertiliser due to improved soil quality (Duan *et al.*, 2014).

Animal and plant production are usually closely connected at the system level. On French dairy farms, more than 80% of the dry matter consumed by the animals is produced on the farm (Rouillé *et al.*, 2014), and more than 60% of the N fertilisation comes directly from livestock manure (Foray *et al.*, 2017). Due to this integration, farm efficiency is related to the feed-use efficiency of the herd, the agronomic efficiency of fertilisers and decreasing N losses during transfer between subsystems and storage. These interactions can improve farm efficiency by up to 40% (Godinot *et al.*, 2015). Farms with the best NUE usually have moderate fertiliser and feed inputs and a stocking rate

adapted to the agronomic potential of the environment (as a function of the climate), while maintaining high milk production (Powell *et al.*, 2010; Thomas *et al.*, 2020). A good match between the animal and crop subsystems can reduce feed and fertiliser purchases by optimising the use of the crops and manure produced. Therefore, mixed crop-livestock systems provide interesting mechanisms for improving NUE (Schröder *et al.*, 2003; Wilkins, 2008; Thomas *et al.*, 2020).

■ 1.3. Regional level

Calculations of NUE at the scale of an agricultural region usually simplify the region into a single farm by default due to a lack of data on the flows between farms. We also adopted this approach because it is not relevant to consider only milk production at the regional scale. NUE is the main efficiency indicator used at this scale (Table 1) and describes the overall efficiency of transforming inputs into agricultural products at the regional scale (Leip *et al.*, 2011; Godinot *et al.*, 2016). It is also used to assess the influence of public policies, such as the European Union (EU) Nitrates Directive, on N management (Dalgaard *et al.*, 2014; Lassaletta *et al.*, 2014).

Identifying synergies between crops and livestock at the regional scale adds mechanisms to those at the farm scale, in particular the complementarity between crop farms and livestock farms due to the exchange of forage, grain, straw and manure. This regional organisation usually addresses the agronomic problems associated with farm specialisation (Ryschawy *et al.*, 2017). Introducing crops or legumes, alone or together, along with catch crops in rotations can improve the NUE of a farm by reducing the purchase of N fertilisers and improving their use by reducing N losses (Martin *et al.*, 2016; Moraine *et al.*, 2016). These types of production are thus ultimately used on nearby farms. Exporting manure from livestock farms avoids potential surpluses and over-fertilisation, and reduces the purchase of fertilisers by the receiving crop farms. Similarly, improving the protein self-sufficiency of livestock farms in a

region by producing protein-rich crops (especially oilseed and protein crops) can improve the overall NUE by reducing imports of concentrates and the use of mineral fertilisers (Russelle *et al.*, 2007). However, these complementarities between crops and livestock can sometimes degrade the NUE of the region. While exporting manure to third parties promotes the intensification of livestock production, if its application is not accompanied by an equivalent decrease in mineral fertiliser application (Regan *et al.*, 2017), then the potential benefit instead degrades the N balance of the region.

Considering the regional scale also enables considering the context in which a farm is located. Efficient N management depends on practices at the farm level, as well as practices on neighbouring farms. Thus, livestock manure is generally used more efficiently when it is spread near to where it is produced. It is not always possible to do so in areas with dense livestock production (Zebarth *et al.*, 1999), which thus requires costly exports. Certain regulations, such as the Nitrates Directive, have resulted in more effective use of livestock manure and a decrease in mineral fertiliser application, which has greatly improved the NUE of the areas concerned (Dalgaard *et al.*, 2014; Buckley *et al.*, 2016). Optimising the distribution of N inputs as a function of the region's production potential would also decrease over-fertilisation and reallocate these resources to less-fertilised areas. This would increase production for a given amount of N use and improve the overall NUE (Ewing and Runck, 2015). This approach can be applied from the scale of a few farms to the global scale (Mueller *et al.*, 2017).

One important mechanism is to use the resources associated with the multiple types of agricultural production in a region, as opposed to the specialisation observed in certain French regions. For example, crop production is generally more efficient than livestock production, poultry production is more efficient than cattle production, and legume production is more efficient than fruit and vegetable production (Godinot *et al.*, 2015). Efficiency can

increase greatly due to the complementarity between crop and livestock production (e.g. consumption of forage legumes or co-products by ruminants, use of livestock manure as fertiliser). A concerted change in production at the regional scale that promotes more diversified and complementary production could thus improve the NUE at the regional scale.

2. Is a system's overall efficiency equal to the sum of the efficiencies of its components?

■ 2.1 Integration at the farm level

Assessment (conceptual modelling based on the "hole in the pipe" principle; Oenema *et al.*, 2009) of the most effective practices identified three strategies that reduce N losses and improve the efficiency of European agriculture: (i) balancing crop fertilisation with good manure management, (ii) reducing the protein content of animal feed and (iii) adopting good manure management practices at building, storage (pit cover) and spreading (direct burial) stages by limiting NH₃ emissions. Combining these practices could improve the European NUE by ca. 25% (Oenema *et al.*, 2009).

However, Faverdin and Van Milgen (2019) present several examples of ruminant and monogastric farming that illustrate how expected benefits can sometimes be lost when changing scale. They indicate that the aggregated approach, based on the assumption that improving each component of a system will improve the overall performance, is not always correct. Conversely, optimising the overall functioning of livestock systems likely provides the most benefits for performance, economics and environmental impacts.

Analysis of experiments at Trévarez, Derval, La Blanche Maison (Chambers of Agriculture of Brittany, Pays de la Loire and Normandy, respectively) and Marcenat (Auvergne, INRAE Herbipôle, <https://doi.org/10.15454/1.5572318050509348E12>) was used to estimate

N flows at the animal and farm scales and identify effects of changing scales depending on the production system (Foray *et al.*, 2017). The experimental farms included systems with a diet based on maize silage and grass (grazed and harvested), from extensive grassland systems at Marcenat and La Blanche Maison 2 (milk production < 5 200 L/ha FA and < 5 300 L/cow) to more productive systems at Derval and Trévarez 1 (> 8 000 L/ha FA and L/cow), in which maize covered a larger percentage of the FA (39% and 50%, respectively; Table 2).

NUE at the animal level varied less among the seven farming systems (23-29%) than NUE at the farm level (23-53%). Thus, “good” efficiency at the animal level did not necessarily translate into better efficiency at the system level, as indicated by comparisons between Trévarez 1 and 2, La Blanche Maison 1 and 2, and Marcenat 1 and 2. These variable efficiencies were not synonymous with a low system N balance or lower N losses to the environment. For example, the two systems at Trévarez had similar NUE, but the N balance of the “maize” system was 22 kg N/ha higher than that of the “maize/grass” system, resulting in higher potential N leaching (+63%). This difference in the N balance was due to the higher N inputs in the “maize” system, particularly of concentrates.

A specific analysis of lowland systems with more than 30% maize in the FA showed that the farms with the lowest N balance also had better NUE (N balance = 79 ± 10 kg N/ha, NUE = $45 \pm 11\%$) than the least efficient systems (N balance = 152 ± 8 kg N/ha, NUE = $28 \pm 6\%$) (Foray *et al.*, 2018). These efficient farms purchased fewer concentrates than the least efficient systems (185 ± 70 vs 231 ± 43 g/L milk, respectively) and N in mineral fertilisers (64 ± 28 vs 110 ± 28 kg N/ha, respectively), which resulted in lower milk production per cow (8%) or per ha (– 15%). These assessments reveal contrasting levels of NUE and N balances among farming systems. However, for a given type of system, careful management of herd feeding and crop fertilisation improves use of N inputs.

■ 2.2 Integration at the regional level

A weighted mean of farm efficiencies does not necessarily predict the efficiency of the region because the flows considered to calculate efficiency are modified by this change in scale. Some exchanges between farms (e.g. straw/manure) are no longer N inputs or outputs but internal flows within the region. It is sometimes difficult to distinguish between feed produced in the region (i.e. internal flows) and feed imported into the region (i.e. inputs). At the farm or regional level, N inputs can increase when local feed resources do not meet the feed needs of the herds, reflecting an imbalance between animal density and the land available to feed them. This lack of feed self-sufficiency requires substantial external purchases, whose surpluses remain in the region. The resulting N balance can thus exceed the region's recycling and recovery capacities and increase the risk of pollution.

As part of a study performed by the Institut de l'Élevage (Foray and Leroy, 2018) for CRESEB (Centre de Ressources et d'Expertise Scientifique sur l'Eau en Bretagne), environmental dimensions of scenarios for improving the efficiency of dairy systems in the Couesnon River catchment of France (Brittany) were assessed. Eleven typical dairy farms were defined at the catchment scale based on an agricultural assessment conducted in 2014. A classification based on 6 technico-economic variables was used to group all the farms into these 11 typical types to estimate the percentage of each typical type at the catchment scale. The indicators calculated at the regional scale were used to analyse the scenarios, and were based on the weighted mean of the representativeness of each type in the region. Environmental analyses of these typical types were performed using the CAP'2ER tool.

Ways to improve these typical types (reflecting the real functioning of the farms surveyed in the agricultural assessment) were identified, which resulted in an optimised scenario. The changes proposed in this optimised scenario resulted in a 13% decrease in the amount of concentrates used per

cow per year for a given production level, and a 17% decrease in application of mineral N fertilisers. In the optimised scenario, the NUE of the types improved by 1-8%, and that of the overall dairy region improved by 4% (Table 3). This improvement in efficiency was due to a decrease in the dependence on inputs imported into the region (i.e. protein concentrates and mineral fertilisers). This optimised scenario also decreased the mean N balance by 15% (from 114 to 97 kg N/ha).

This theoretical analysis shows that specific measures implemented at the scale of each of dairy system would improve their efficiency and reduce losses at the local and regional scales. Optimising N management among systems could further improve this efficiency, but the actual relevance of these approaches remains difficult to verify in the field.

3. Relations between efficiency and environmental impacts

Two main strategies improve efficiency regardless of scale: increasing output for a given amount of (or small increase in) input, or reducing inputs with little or no decrease in output. These two strategies usually correspond to differences in economic reasoning, as observed in EU member states. Regardless of the strategy chosen, this synthesis shows that different mechanisms exist for improving the “system” (e.g. animal, subsystem, farm, group of farms), increasing efficiency and reducing losses. For farmers, a decrease in production is often perceived as an obstacle to implementing good practices. However, due to the high marginal cost of the last kg produced, decreasing inputs often compensates for a decrease in revenue (Pellerin *et al.*, 2013). From an economic viewpoint, this “input-saving” strategy amounts to increasing the gross operating surplus (GOS)¹ by minimising expenses

¹ The gross operating surplus (GOS) equals the gross product (sales + subsidies ± changes in inventory) minus operating and structural costs (excluding depreciation and financial costs).

Table 2. Descriptions, nitrogen (N) balances and N-use efficiencies of seven dairy systems monitored on four experimental farms in France: Trévarez, Derval, La Blanche Maison and Marcenat (adapted from Foray et al. 2017).

Experimental farm	Trévarez 1	Trévarez 2	Derval	La Blanche Maison 1	La Blanche Maison 2	Marcenat 1	Marcenat 2
Forage system	Maize	Maize/grass	Maize	Maize	Grass	Grass	Grass
Years monitored	2013-2014	2013-2014	2011-2014	2011-2014	2011-2014	2011-2012	2011-2012
Maize in FA ¹	50%	26%	39%	32%	0%	0%	0%
Number of cows	55	63	89	35	35	22	22
Milk produced/cow (L)	8 118	7 311	8 544	6 121	5 285	5 023	5 260
Milk produced/ha FA (L)	9 112	7 613	8 068	7 142	5 139	1 796	3 969
Livestock units/ha FA	1.64	1.51	1.30	1.80	1.40	0.63	1.05
Nitrogen balance and nitrogen-use efficiency at the dairy cow level (kg N/cow/year)							
Forage N intake	102	139	88	83	115	109	91
N in ingested concentrates	46	29	86	70	23	0	15
Total N intake	148	168	174	153	138	109	106
Milk protein N content (g/kg)	31.2	30.3	32.8	34.9	34.2	30.4	31.5
N in milk and meat	42	38	49	45	39	28	31
Animal N balance	106	130	125	108	99	81	75
Feed NUE	28%	23%	28%	29%	28%	26%	29%
Nitrogen balance and nitrogen-use efficiency at the system level (kg N/ha utilised agricultural area)							
Total N inputs	238	190	152	174	127	25	105
<i>of which N in forage and concentrates</i>	93	44	80	99	46	2	21
<i>of which N from symbiotic fixation</i>	32	36	31	40	44	12	27
<i>of which N in mineral fertilisers</i>	42	38	31	0	0	0	47
Total N output	121	95	54	66	56	12	24
System N balance	117	95	98	108	71	13	81
Potential N leaching	44	27	34	18	10	0	0
Nitrogen-use efficiency	51%	50%	36%	38%	44%	48%	23%

¹ FA: forage area.

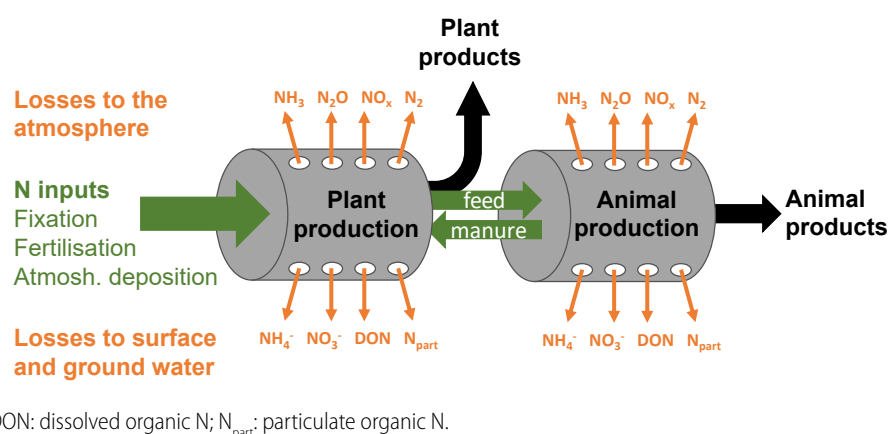
Table 3. Characteristics of the mean dairy system, nitrogen-use efficiency and the nitrogen (N) balance of the Couesnon River catchment of a baseline scenario and a scenario with optimised fertilisation and feeding for 11 dairy-system types in the region (from Foray and Leroy 2018).

Characteristic	Scenario	
	Baseline	Optimised
Grass area in total UAA ^(a)	38%	38%
Maize silage area in total UAA	30%	30%
Cash-crop area in total UAA	32%	32%
FA in total UAA	68%	68%
Stocking rate (LU/ha FA ^(b))	1.84	1.83
Milk yield (kg/ha FA)	9 304	9 295
Milk yield (kg/ha UAA)	5 636	5 636
Concentrates fed (kg/cow)	1 479	1 282
Concentrates fed (g/L milk)	196	170
Total N inputs (kg N/ha UAA)	191	175
of which N from concentrates (kg N/ha UAA)	83	79
of which mineral N fertilisation (kg N/ha UAA)	62	51
Total N output (kg N/ha UAA)	77	78
N balance (kg N/ha UAA)	114	97
N-use efficiency	40%	44%

^(a)UAA: utilised agricultural area.

^(b)FA: forage area; LU: livestock units.

Figure 3. Nitrogen (N) flows at the farm level according to the “hole in the pipe” model (adapted from Oenema et al. 2009).



(Réseau CIVAM, 2021). Conversely, the objective of the “productive” “strategy” is to maximise GOS by increasing the gross product (GP). The economic benefit of these strategies can be assessed from changes in the GOS:GP ratio. In a recent study that compared economic and environmental efficiencies of dairy systems, the GOS:GP ratio was $35 \pm 9\%$ for input-saving farms but $30 \pm 9\%$ for productive farms (Castellan *et al.*, 2021). Although input-saving farms had worse NUE than productive farms (35% vs 39%, respectively), they had a lower N balance (95 and 125 kg N/ha, respectively). Another strategy accepts a greater loss of production while promoting higher-quality and higher-value products (e.g. products with quality labels) due to a higher sales price. In this case, NUE can be the same as that of productive systems, N losses are usually lower (N balance = 60 kg N/ha), and economic efficiency is improved (GOS:GP ratio = $39 \pm 9\%$; Castellan *et al.*, 2021).

The “hole in the pipe” model (Oenema *et al.*, 2009) is useful for analysing differences in the behaviour of these NUE and N-loss indicators. According to it, N inputs, outputs and losses in agricultural systems are not independent: a change in one flow can influence those that follow it (Figure 3). Thus, applying a mechanism to improve NUE and decrease the N balance at a given level (“plugging a hole”) could increase N losses at a larger level of organisation and thus degrade the NUE of the overall system.

In Ireland in the 2010s, the NUE of dairy systems improved (from 19.7% to 24.4%) but the N balance increased (from 154 to 179 kg N/ha; Dillon *et al.*, 2020), which indicates more N losses to the environment. Similarly, dairy systems in the Netherlands are among the most efficient, but they also have the highest N balances. Dairy systems monitored in the EU H2020 project EuroDairy indicated that some of those that used large amounts of inputs (> 700 kg N/ha) had N balances greater than 500 kg N/ha (Foray *et al.*, 2019). These observations agree with those of the EU Interreg project Green Dairy in the early 2000s (Raison *et al.*, 2008). Conversely, farms in western France are less efficient but lose less N due to lower input use (Quemada

et al., 2020). For example, specialised dairy farms in Brittany reduced mineral fertilisation by 50% from the mid-1990s to 2010 in response to regulations introduced by the Nitrates Directive, the establishment of vulnerable zones and associated action programmes. Improved fertilisation management and more recognition of the value of livestock manure as an organic fertiliser have been accompanied by better agronomic practices, which has improved NUE by from 27% to 39% and reduced the N balance from 143 to 93 kg N/ha. This result partly reflects a decrease in waste caused by substantial over-consumption of N inputs.

At the regional level, the efficiency and impacts of production systems are not inherently related. Their relationship depends primarily on the density of livestock production and thus on the ability of the environment to support it. A few inefficient farms in an area with low livestock density will often have a moderate impact in the region because they are “diluted” over a large area. This occurs in Portugal and some regions of Spain and Scandinavia. However, efficient farms can have more impact on terrestrial and aquatic environments, such as in the Netherlands and Belgium, where emissions to the water and air are higher because they have a high animal density, despite having better NUE than those of other European countries (Godinot *et al.*, 2016).

The potential environmental impact of this N surplus depends on the sensitivity of the environment (e.g. climate conditions, soil types), especially its capacity to recycle and use the N from livestock farms, which can depend on the soil and climate context as well as farming practices (Peyraud *et al.*, 2012b). In highly grazed livestock farming areas, nitrate leaching is often minimal and has little effect on water quality. This is true in the Massif Central, the Alps, Burgundy and Limousin regions, which are dominated mainly by grassland cattle farming and have some of the lowest nitrate concentrations in surface and ground water in France (Foray and Manneville, 2019).

Conversely, in certain highly intensive grassland systems per ha (but not per cow), such as in New Zealand,

milk production increased by more than 5 000 L/ha from the 1990s to the early 2010s due to an increase in use of concentrates and mineral fertilisers. This intensification increased the N balance (+ 60 kg N/ha) and N leaching (+ ca. 8 kg N/ha) and degraded water quality (Richard *et al.*, 2017). Regional plans for freshwater management have been implemented to limit these risks of losses and to stop the degradation of water quality.

The Green Dairy project also showed that nitrate leaching was greater in dairy systems based on forage crops with rapid rotations such as grasslands/crops (e.g. in France, Netherlands), despite lower N balances and/or better NUE than those of grassland systems based on more perennial grasslands (e.g. in Ireland). Thus, although N balances may be similar, the influence of agricultural practices and the sensitivity of the environment will result in different environmental impacts (Figure 4).

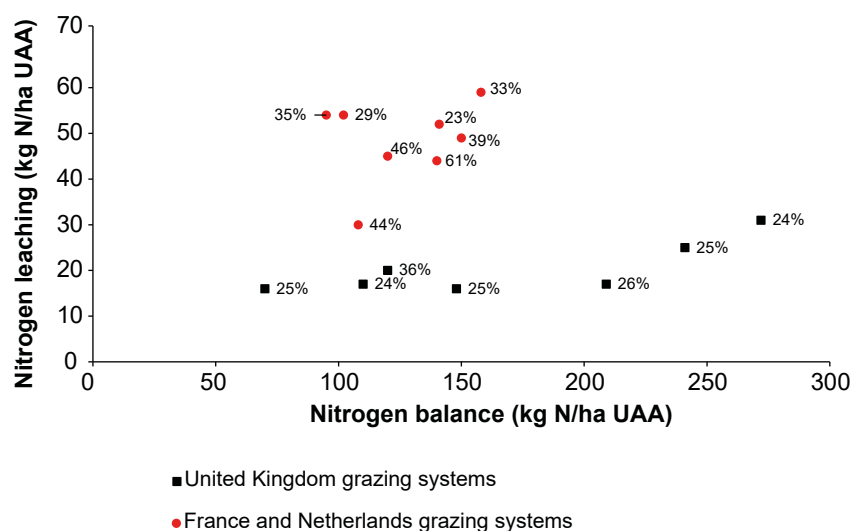
4. Utility and limitations of nitrogen-use efficiency indicators

Efficiency seems to be a relatively simple criterion to calculate and use to optimise a system at a given time and

spatial scale. However, it is important to verify that practices that are more efficient at the animal or field level remain useful at the farm or regional level. Moreover, efficient farms can generate high environmental impacts. This is usually true for the most intensive farms, on which the stocking rate exceeds the production capacity of the associated land and requires importing inputs, some of which are not used and thus degrade the environment. Thus, efficiencies must always be interpreted in relation to the N balance (Godinot *et al.*, 2014; EU Nitrogen Expert Panel, 2015). For example, NUE does not consider N losses associated with the manufacture of purchased inputs (e.g. feed, fertilisers) or changes in soil N stocks (Godinot *et al.*, 2014). Recent studies recommend changing the calculation of NUE to correct the main biases (Quemada *et al.*, 2020) and avoid externalising impacts to other regions (e.g. those that produce imported feed).

NUE's main advantage is that it focuses on a single element, which makes it a relatively simple indicator to calculate, understand and compare. However, this also becomes its main limitation when trying to understand other important dimensions of dairy farming, such as greenhouse gas emissions and carbon sequestration,

Figure 4. Nitrogen (N) leached as a function of the farm-level N balance for grassland systems in the United Kingdom (UK), France and the Netherlands (Raison *et al.*, 2008).



The point labels indicate the nitrogen-use efficiency (NUE) of the system. The UK grassland systems were based mainly on permanent grassland, whereas the French and Dutch forage-crop systems were based mainly on temporary grassland that was resown regularly. UAA: utilised agricultural area.

the maintenance of biodiversity, the contribution to employment or landscape maintenance, or the nutritional or cultural value of dairy products. The NUE and N balance indicators aggregate all forms of N into a common unit (kg N), which facilitates analysis and comparison of production systems and provides an integrated view of agricultural production and its impacts. However, these indicators cannot distinguish the forms of N lost (e.g. NH_3 , nitrate, N_2O). Some practices that reduce nitrate losses could increase losses of N_2O or NH_3 (the “hole in the pipe” model; Figure 3). Thus, it is necessary to consider integrated N management and the multiple impacts caused by N losses in different forms at different scales. Life-cycle methods are good approaches to address this limitation.

NUE has attracted political interest due to its relevance and relatively simple calculation at different spatial and temporal scales. However, crop production often has much better NUE than livestock production, even though new approaches and consideration of the proportion of crop production that humans cannot consume directly now provide a new, more positive view of the efficiency of livestock production (e.g. “net” efficiency, Laisse *et al.*, 2018). Consequently, at the regional or country scale, the main factor that influences efficiency is the relative proportions of crop and livestock production (Leip *et al.*, 2011; Godinot *et al.*,

2016). For a country such as France, the national mean efficiency masks large differences among regions due to different soil and climate contexts and agricultural orientations. Thus, it is challenging to recommend a national or even regional efficiency threshold without considering the type of agricultural production, agronomic potential and sensitivity of natural environments to pollution. A relative efficiency indicator was developed to address this limitation (Godinot *et al.*, 2015). It demonstrates benefits of researching efficiency indicators to improve them and adapt them to different uses, from agricultural advice at the farm level to global environmental assessments and regional, national or European public policies.

Conclusion

Improving the NUE of cattle farming is often recommended to improve the environmental profile of animal products (milk and meat). This synthesis highlights that many mechanisms exist at different scales to better use N resources in dairy systems, and thus improve the latter’s efficiency. These mechanisms can often reduce N losses to the environment as well as production costs, especially by reducing inputs. However, efficiency cannot be addressed alone due to the risk of encouraging the intensification of systems without reducing losses, as

observed in some European countries. Similarly, at the regional level, seeking maximum efficiency could lead to standardising production systems, which would have negative consequences on environmental, economic and social dimensions. Relocating farms to low farm-density areas, which seems attractive due to its positive impact, is difficult to envision without a strong incentive policy. Redistributing N and other nutrients by transferring animal waste, another product of livestock farming with multiple agronomic benefits, to crops and between regions should be encouraged to close nutrient cycles and develop a circular bioeconomy. N management must improve N use at all levels, as well as their interactions, to reduce waste, and decrease N losses to ensure a good environmental status. Therefore, NUE and the N balance are essential and complementary indicators.

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Abstract

Improving the use of nitrogen at all stages of its use is a priority, especially in livestock systems where it remains relatively low. There are many nitrogen use efficiency indicators based on various calculations depending on the context and the scales considered. The literature is full of examples of win-win practices improving its use and reducing its losses to the environment. But few studies present an integrative view of these gains at supra scales. This article first recalls the main strategies for increasing nitrogen use efficiency at the animal, farm and territory levels. The analysis of the integration of gains at global levels shows that improving efficiency at a given scale does not systematically generate an efficiency gain at larger scales or for the whole system. Moreover, the search for high efficiency does not always allow a reduction in nitrogen losses, some of the most efficient systems are also those that generate the highest impacts, a consequence of the high levels of N used. Efficiency indicators remain useful tools for improving nitrogen use in agricultural systems, but should be consistently associated with nitrogen loss indicators to better consider the consequences of agricultural systems on the environment.

Résumé

De l'animal au territoire, regards sur l'efficacité de l'azote dans les systèmes bovins laitiers

Améliorer la valorisation de l'azote à toutes les étapes de son utilisation est une priorité, notamment en élevage où elle demeure relativement faible. Les indicateurs d'efficacité azotée sont nombreux et basés sur des méthodes de calculs diverses selon le contexte et les échelles considérées. La littérature illustre un certain nombre de pratiques vertueuses, le plus souvent applicables à l'échelle de l'animal ou du troupeau, qui en améliorent la valorisation. Mais peu d'études présentent une vision intégrative de ces gains aux niveaux d'organisation supérieurs comme l'exploitation ou le territoire. Cet article rappelle tout d'abord les principales stratégies qui permettent d'augmenter l'efficacité d'utilisation de l'azote à l'échelle de l'animal, de l'exploitation et du territoire. L'analyse de ces gains à différentes échelles met en évidence qu'une amélioration de l'efficacité à un niveau donné n'induit pas systématiquement un gain d'efficacité à l'étage supérieur ou pour l'ensemble du système. Par ailleurs, la recherche d'une efficacité élevée ne garantit pas systématiquement une réduction des pertes azotées vers l'environnement : certains systèmes d'élevage les plus efficaces sont aussi ceux qui génèrent le plus d'impacts du fait des quantités importantes d'azote utilisées. Les indicateurs d'efficacité s'avèrent des outils utiles pour améliorer l'utilisation de l'azote dans les systèmes agricoles, mais ces ratios ne disent rien des quantités mises en jeu tant au numérateur qu'au dénominateur. Ils devraient donc être systématiquement associés à des indicateurs de pertes azotées pour une meilleure prise en compte des conséquences des systèmes agricoles sur les milieux naturels.

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