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Comparison of nitrogen fertilisation recommendations of West European Countries

Running title: Nitrogen fertilisation recommendations in Europe

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Abstract

Nitrogen (N) budgets at farm level are influenced by N fertilisation recommendations. In this study, we reviewed and analysed the underlying principles and methods of N fertilisation recommendations in ten West European countries, to identify similarities and differences, and develop suggestions for reconsideration and improvement. An analysis of national official documents on N fertilisation recommendations revealed that there were three main categories of calculation methods: (i) ‘N mass balances’ (France, Italy, Spain), (ii) ‘Corrected standards’ (Germany, Netherlands, Switzerland, Luxembourg), and (iii) ‘Pre-parameterised calculations’, which rely on a soil N supply typology (United Kingdom, Ireland, Belgium). In total 16 variables were identified in the calculation methods. The more complex methods use 10 (Italy, France), while the simplest only rely on 3 (Luxembourg). The most common variables include the availability of N in manure, the N uptake by a crop, and the N released by crop residues. Few countries explicitly consider N losses to ground and surface waters or to the atmosphere in the calculation methods. In some countries, the N fertilisation recommendation has a voluntary status, in other countries a legal one (caps on maximum allowable N rates). We compared the N fertiliser recommendations for a wheat crop grown on a farm with livestock, and for a farm with a diverse arable crop rotation without livestock. Across the 10 countries, large differences in the N fertilisation calculation methods and resulting N recommendations existed for the two management scenarios, ranging from almost no fertilisation to 135 kg N ha^{-1}, and from 111 to 210 kg N ha^{-1}, respectively. The differences were not accounted for by the complexity of the equations used, but rather resulted from contrasting reference values for N availability in manure, N uptake by crop and N leaching.

However, the study concluded that standardisation of the method to calculate N fertilisation recommendations is likely to be counterproductive as there are no objective reasons to favour one method more than the others. Nonetheless, improvements in N use efficiency are necessary. Farm scale mass balance, combined with parameters such as minimum residual soil mineral N test at harvest was suggested as being an important consideration.

Keywords: advice, fertilizer guide, harmonisation, innovative approaches, mass balance, nitrate, regulation,

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Highlights

1. West European countries use up to 16 parameters to achieve the calculation of N fertilisation rates
2. N losses (air, water) are sparsely taken into account in the mass balance equations
3. A case study applied to 10 countries exhibited recommended rate differences of up to 100 kg N ha^{-1}
4. N uptake by crops and available N in manure exhibit large discrepancies among countries

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1. Introduction

The generation of mineral N fertilisers via the Haber-Bosch process has facilitated the spectacular increase in crop and animal production since the 1950s, and resulting N fluxes to and from soil (Erisman *et al.,* 2008; Galloway *et al.,* 2013). However, the use of N by farmers is far from being 100% efficient. A recent European survey (EU-28, Eurostat, 2020) reported that only 61% of the N applied (organic + mineral) was used by plants, with great variations between countries. For example, the efficiency gap between Ireland and Luxembourg reaches 30%, with efficient N use estimated at 80% and 50%, respectively. As a result, the gross nitrogen balance for agricultural land exhibits an average excess of 50 kg N per ha per year, but with wide variation between countries and between farming systems (Eurostat, 2020).

Concurrently, N fluxes to waterbodies have doubled within the last century (Sutton and Billen, 2011), and emissions to the atmosphere have increased by a factor of four. Therefore, most parts of our environment have been facing excess N concentration, for decades (Steffen *et al.,* 2015). As a result, the nitrate concentrations in ground- and surface-waters have exceeded the standard for drinking water in several regions and have contributed to the eutrophication of coastal areas. In addition, emissions of ammonia (NH_3) and nitrogen oxides (NOx and N_2O) to air are contributing to deteriorating air quality and biodiversity in natural ecosystems, and enhancing global warming (Sutton *et al.,* 2011).

Within the European Union (EU-28), the current annual mean nitrate concentrations for ground water and rivers is around 20 mg NO_3^- L^{-1} and 2 mg NO_3^- L^{-1}, respectively. The European statistics on water quality point out that those values have evolved without measured improvement for the last 30 years (European Environment Agency, 2022). According to a N transfer model run by de Vries (2019), the risk of eutrophication of waterbodies is the most critical threat and necessitates a reduction in the N-leakages from fields by a factor of two, based on a critical N concentration of 11 mg NO_3^- L^{-1} (2.5 mg N L^{-1}).

Assessing the consequences of atmospheric N emissions to ecosystems and humans seems more complicated than assessing the consequences of high nitrate concentrations in water bodies. However, their effects should not be underestimated. For example, at the EU scale, the annual mortality linked to the fine particulate matter in air ($PM_{2.5}$, caused in part by NH_3 and NOx emissions) is estimated at around 300,000. The contribution of nitrous oxide (N_2O), emitted by soils from fertiliser and manure use contributes 5% to the total greenhouse gas emissions in Europe (European Environment Agency, 2011). Awareness of these concerns has led the European Union to develop environmental Directives, firstly targeted on water bodies (Nitrate Directive 1991/676/EEC, and the 2001 Water Framework Directive), and the atmosphere (Directive 2008/50/EC on ambient air quality and cleaner air for Europe). More recently, the ‘Farm-to-Fork’ strategy, standing for the agricultural implementation of the ‘Green Deal’, is particularly focusing on nitrogen losses with the aim of a 50% reduction within the next ten years (European Commission, 2020). In this context, N fertilisation recommendations for farmers (including organic products) represent a potentially very powerful lever of action, as any excess of fertilisation for one given crop is potentially lost, therefore supplying water bodies, atmosphere and natural ecosystems with ‘non-intended’ fluxes.

This study aimed to review and test the nitrogen fertilisation recommendations available to farmers across ten West European countries (Belgium, France, Germany, Ireland, Italy, Luxembourg, the Netherlands, Spain, Switzerland, United Kingdom). The objective was to detect innovative approaches, original calculations and references that could be shared among countries having equivalent crop practices, and, eventually, by improving N use efficiency, help to achieve a reduction in N losses of 50%, as expected by the ‘Farm-to-fork’ strategy. Our analysis was mainly based on a theoretical approach (fertilisation calculation methods used within ten European countries, described within technical grey literature) applied to two contrasting farming scenarios; a wheat crop grown on a livestock farm and receiving manure applications; and a wheat crop grown on an arable farm with no livestock and no manure applications.

2. Material and methods

2.1. Origin and geographic scales of information

We focussed our survey on data from national or regional extension services, which are providing advice to farmers, but also included data from scientists directly involved in the development of the calculation methods and N fertilisation recommendations in their specific countries. We complemented this information with personal contacts established through the list of contributors within the European Joint Program for Soil (EJP-SOIL) ‘Towards climate-smart sustainable management of agricultural soils’, deliverable 2.4.5 (Stocktake study and recommendations for harmonizing methodologies for fertilization guidelines, Higgins *et al.*

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2023), making it possible for us to access some ‘grey’ literature, such as brochures detailing the calculation methods. Data were obtained from the following countries: Belgium, Germany, Ireland, Italy, Luxembourg, the Netherlands, Spain, Switzerland and United Kingdom. Table 1 summarises the national and regional references, which gave information on the calculation rule for N recommendations. We applied original or operational information currently in use by each country, summarized as selected equations or tables.

Table 1: Names and origins of the national official documents governing the N fertilisation in some west European countries.

Country	**Names of the national official documents** (in their original language)	**Last update**	**Reference**
Belgium (Wal.)	Prog. de Gestion Durable l’Azote en région wallonne (version 4) Etablissement du conseil de fumure azotée en	2023 2021	Walloon Government ASBL REQUASUD
France	Calcul de la fertilisation azotée. Guide méthodologique pour l’établissement des prescriptions locales	2013	COMIFER[1]
Germany	Verordnung über die Anwendung von Düngemitteln. Düngeverordnung - DüV	2020	German Ministry services
Ireland	Major & micro nutrient advice for productive agricultural crops, 5th Ed	2020	Wall & Plunkett, Teagasc, Wexford
Italy	Linee guida nazionali di produzione integrata	2020	Ammassari P., Ministry of agriculture and forestry
Luxembourg	Ordonnance régissant l'utilisation de fertilisants azotés dans l'agriculture	2014	Règlement grand-ducal modifié du 24 novembre 2000
Spain	Guia Practica de la fertilizacion racional de los cultivos en Espagna	2012	García A.C., . Ministry of the Environment and Rural and Marine Affairs
Switzerland	Principles of fertilisation of agricultural crops in Switzerland	2017	Sinaj S. & Richner W. Agroscope, Swiss Confederation
The Netherlands	Handboek Bodem en Bemesting	2020	de Haan J.J. Arable Fertilisation Committee
United Kingdom	Nutrient Management Guide (RB209)	2020	AHDB[2], BBRO[3], PGRO[4]

[1] COMIFER Comité français d'étude et de développement de la fertilisation raisonnée

[2] AHDB Agriculture and Horticulture Development Board

[3] BBRO British Beet Research Organisation

[4] PGRO Processors and Growers Research Organisation

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2.2. Comparing N recommendations by running each national equation / procedure

The objective was to compare the N recommendation output for each of the country-specific N calculation methods when applied to two case study (farming system) scenarios. The comparison of the recommended rates of N fertilisation required erasing as much as possible the cropping and pedoclimatic specificities between the ten countries. Therefore, we chose one of the most common soils, a non-calcareous deep silty-clay alluvium (Table 2). We tested two different farming systems widespread in Western Europe, based on the wheat crop. The two cropping systems not only differ with the kind of fertiliser used, but also with the type of rotation, target yield, etc. (Table 3). No statistical treatment was applied to the data, as we obtained only one value of N recommendation per country and per farming system. Moreover, none of the national methods provided any confidence interval to their results. The significance of the differences between countries was therefore impossible to establish.

Table 2: Soil characteristics of the wheat field used for the simulations

Soils parameters	**Units**	**Soil sampling depth**	
		0-30cm	**30-60 cm**
Fraction >2mm	*g kg^{-1}*	0	0
Clay		194	163
Fine silts		215	188
Coarse silts		324	360
Fine sands		196	220
Coarse sands		52	60
Total $CaCO_3$		0	0
Active $CaCO_3$		0	0
Organic C		10.3	4.2
Organic Matter		17.7	7.2
Total N		1.0	NA
pH		6.5	4.7
C/N		10.8	NA
CEC Metson	*cmol kg^{-1}*	9.7	5.4
Saturation of CEC	%	99	86
Density	*g cm^{-3}*	1.3	1.4

CEC: Cation exchange capacity, NA: data not available

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Table 3: Description of the two wheat crop system scenarios for the calculation of the recommended N rate

	Type of farming system	
	Arable	**Crop, livestock**
Main crop	Wheat (for cattle feed)	
Target Yield[1]	7 tons ha^{-1}	5 tons ha^{-1}
Key-depths	Root depth: 60cm Ploughing depth: 30cm	
Key-dates	Sowing: 15th October Harvest: 15th July	
Winter Rainfall (1st Oct-1st March)	400 mm	
Straw management	Left on the field	Exported
Preceding crop	Rapeseed (4 t ha^{-1}) [2]	Grass ley (2 years), mown + grazed
Cover crop	Phacellia / Brassica [3]	
Manure		15 tons ha^{-1} FYM [4]

[1] 15% moisture

[2] fertilised with 140 kg N ha^{-1}

[3] early October destruction

[4] 5.5 kg N ton^{-1} of fresh weight of Farm yard manure spread in September, with a frequency of once every three years.

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Table 4: Components (inputs and outputs) included in the nitrogen budget by each country, ranked in decreasing order of number used.

	Outputs (direct or through coefficient)					Inputs (or not needed to be brought)											Number of variables (except AUC)
	S_{end}	C_{end}	L	A	AUC	S_{start}	C_{Start}	Hu	Past	CR	IC	Ir	M_1	M_{n-1}	Atm D	AdY	
	Soil end	Uptake	Leaching	Atmos. Loses	Apparent Use Coefficient	Soil start	Crop start	Humus min.	Pasture min	Crop residues	Interm. crops	Irrigation	Manure	Manure Year-1	Atmos. deposition	Adjust. of the yield	
France	■	■			■	■	■	■	■	■	■	■	■				10
Italy		■	■	■		■		■		■	■		■	■	■		9
Switzerland		■	■					■	■	■	■		■	■		■	9
Belgium (Wal.)		■				■	■	■	■	■	■		■	■			9
Germany		■				■		■	■	■	■		■	■		■	9
United Kingdom		■	■		■	■	■	■	■	■			■				8
Spain	■	■	■		■	■				■		■	■		■		8
The Netherlands	■	■				■	■	■		■			■			■	8
Ireland		■							■	■	■		■			■	6
Luxembourg		■											■			■	3

Output parameters

S_{end}	Soil mineral remaining at harvest;
C_{end}	Whole crop total nitrogen at harvest, including roots and annually adjusted to quality and variety criteria for cereals;
L	Leaching;
A	Atmospheric losses (denitrification, volatilisation);
AUC	Apparent Use Coefficient, standing for the uptake efficiency of the mineral fertiliser provided. Depends on local conditions (crop stage, climate …) prevailing during mineral spreading;

Input parameters

S_{start}	Soil mineral N at sowing (or starting point of mass balance) generally measured in fields, but possibly computed for difficult sampling conditions;
C_{Start}	Nitrogen already taken up at the starting point (e.g. time of spring soil sampling), generally negligible except for winter rape;
Hu	Nitrogen net release from soil organic matter (humus mineralisation);
Past	Nitrogen net release from soil organic matter, following grasslands ploughing;
CR	Effect of previous crop residues, depending on the type of residues;
IC	Effect of catch crops or green manure;
Ir	Nitrogen supplied by irrigation water;
M_1	Nitrogen from the organic manure contribution, either calculated from the inorganic fraction and an estimate of the organic release during the season, or through apparent nitrogen recovery coefficients;
M_{n-1}	Nitrogen derived from the mineralisation of organic amendments brought the years before;
Atm D	Atmospheric deposition of nitrogen, generally under ammoniac deposition;
AdY	Effect of factors that increase or decrease crop demand (C_{end}); can be an input or an output to the mass balance, depending on the yield reference

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3. Results

3.1. N recommendation rates: theoretical approaches by national extension services

The following results are ranked by decreasing order of complexity of the methods, i.e. the number of variables taken into account to achieve the calculation of the advised N fertilisation rate. The chosen illustrations provide some specific examples for each country. Special attention is paid to the level of integration of the recommended rates into the legal enforcement of nutrient management of every country. We analysed to what extent the fertilisation recommendations were serving as official references (even partially) for regulatory controls towards the Nitrate Directive.

3.1.1. France

In France, fertilisation recommendations for the main crops are based on an N-balance equation at the field scale. The generic equation is described in a national reference guide edited in 2013 by the COMIFER ('French Committee for the Study and Development of sustainable Fertilisation', Table 1). Including at least 20 parameters, the theoretical equation is inappropriate in its complete form, from a practical point of view. Therefore, it is accompanied by simplified forms, to cope with the lack of information, e.g. volatilisation and denitrification rates, leaching, etc. In simple terms, the equation can be reduced to very few terms, with the unknown variables being merged into an 'Apparent Use Coefficient' (AUC), standing for the uptake efficiency of the mineral fertiliser provided. For secondary crops for which there are a lack of references, official recommendations rely on 'standard' doses, adjustable to particular conditions ('doses pivot', e.g. sunflower, soybean) or a maximum thresholds ('plafonds', e.g. vegetables, fruit trees, vineyards).

Each of the twelve French regions are obliged to choose the equation that suits their cropping system best and locally available parameters. For example, in the Nouvelle Aquitaine region, the equation used by farmers combines input and output variables, as well as the use of the efficiency coefficient (AUC) (Eqn 1). It is described at regional levels, with online information available derived from a Regional Nitrate Expertise Group (GREN):

$$N_{rate} = [(C_{end} + S_{end}) - (S_{start} + C_{Start} + Hu + Past + CR + IC + Ir) - M1] / AUC \quad \text{Eqn 1}$$

Explanation of symbols are given in Table 4. The specifics for France are:

- the crop N content at harvest (C_{end}) accounts for the whole crop, including roots and is annually adjusted to quality and variety criteria for cereals; it is defined for every crop per yield unit;
- the soil mineral N is the starting point of the mass balance (i.e. sowing or end of lixiviation period, S_{start}) and is generally directly measured in fields, being one of the compulsory measurement advised in the Nitrate Vulnerable Zones (or estimated for difficult sampling conditions thanks to fields reference network);
- the N already taken up at the starting point (C_{Start}) is generally negligible except for winter rape;
- the effect of intermediate crops (IC) harvested before the starting date of balance calculation can be experimentally estimated by the 'MERCI' tool (Constantin *et al.,* 2023) from gross weighting at the harvest of the intermediate crops;
- ACU: Apparent Use Coefficient, represents the uptake efficiency of the mineral fertiliser applied. It depends on the crop conditions (plant stage, climate, etc.) prevailing during at mineral spreading.

For every region, the use of the mass balance equation or any equivalent calculation tool is mandatory, but not the dose itself. This is partly because the current equation cannot estimate the precision of the final value. So far, there is no threshold gap between the calculation performed by the assessor and the one made by the advisor or the farmer himself. The calculation tools that are officially used to perform the mass balance calculation receive a special label ("Prev'N") delivered by the COMIFER.

3.1.2. Italy

The Italian N fertilisation approach is based on a mass balance at the field scale. The mass balance is described in the national guide ('National guidelines for integrated crop production, 2020'), providing 'default values' unless Regional brochures are used. The approach is quite mechanistic, as most of the variables depend themselves on secondary factors, as shown below (Eqn 2). Several measurements are required, such as soil texture, organic matter content and C/N ratio.

$$N_{rate} = C_{end} + L + A - (S_{start} + Hu + CR + M1 + Mn\text{-}1 - Atm\ D) \qquad \text{Eqn 2}$$

Explanation of symbols is given in Table 4. The specifics for Italy are:

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-The soil mineral nitrogen at sowing (S_{start}) is calculated from a combination of soil texture and total soil N content;

- The N provided by humus mineralisation (Hu) is a combination between soil texture, C/N ratio and the organic matter content, and is proportional to the duration of the crop growing period;

- The N exported by leaching (L) can be either estimated by the cumulative winter rainfall between the 1st of October and the 31st of January (i.e. no leaching below 150 mm and no N left if rainfall is greater than 250 mm), or can be deduced from the combination of soil drainage class and soil texture;

- The N lost by denitrification and volatilisation (A) and immobilised is proportional to the soil N availability, defined as Hu + S_{start}. Proportionality coefficients vary from 15 to 40% according to the drainage class and the soil texture.

- The N derived from manure applied before sowing (M_1) is calculated by multiplying the amount of manure-N applied by a tabbed apparent N recovery coefficient, which depends on manure type, soil texture, manure N rate, application date, and application method.

- The N derived from the repeated application of manure in previous years (M_{n-1}) depends on the frequency of spreading and on manure type (Table 5).

Table 5: Percentage of annual recovery of the total amount of N applied in function of the frequency of repeated manure spreading in previous years in Italy (National guidelines for integrated crop production, 2020)

Type of manure spread	**Frequency of inputs**		
	Every year	1 year out of 2	1 year out of 3
	%		
Solid manure	50	30	20
Liquid manure (dairy)	30	15	10
Liquid manure (pork & poultry)	15	10	5

From a regulatory point of view, the N recommendation issued with this budget is part of a set of prescriptions to farmers who voluntarily accept to follow the Italian certification system of integrated production. Alternatively, in terms of the detailed N budget, the recommended N

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rate is defined based on a 'standard dose' for each crop, established and approved at the national level. These standard N rates can be adapted by regions and autonomous provinces according to specific territorial characteristics. Each standard N rate refers to a reference situation (expected crop yield), and is adjusted by the advisor depending on the specific situation, still using tabbed options (e.g. the rate is lowered after an alfalfa crop, or is increased for bread-making wheat). If verification organisms certify the proper implementation of the rules for integrated production (including the application of the recommended N rate), farmers can use the national label of 'Integrated Production' on their products, and/or can obtain funding within the Rural Development Programme (for specific operations) or common market organisations.

3.1.3. Switzerland

The Swiss method is described in the national guideline, 'Principles of fertilisation of agricultural crops in Switzerland' (Sinaj and Richner, 2017), edited by AGROSCOPE, the Swiss centre of excellence for agricultural research . The recommended rate of N fertilisation is based on a 'reference dose', also called standard fertilisation ($N_{rate\ std}$); it corresponds, for a given crop, to the quantity of N that must be provided to obtain the average yield or reference yield observed in Switzerland for this crop. Fertilisation standards and yield references result from experiments establishing the crop response curve to fertilisation N, farmers' experience and expert knowledge (Richner *et al.,* 2010, Maltas *et al.,* 2015). Therefore, the modified dose is calculated as follows:

$$N_{rate} = N_{rate\ std} + (AdY + Hu + CR + IC + M_1 + M_{n-1} + L) \qquad \text{Eqn 3}$$

Explanation of symbols are given in Table 4. Most of the correction factors are quite similar to those developed in other countries. It is however worth noting that corrections due to the mineralisation potential are not only a function of clay and organic matter content (Table 6) but also vary according to the frequency of mechanical weeding, thus providing the crop with an addition of 10 to 20 kg N ha^{-1}. M_1 is considered depending on fertiliser selection estimating the in season available N content. In Switzerland the $N_{rate\ std}$ is the aboveground N offtake at harvest.

Alternatively, it is also possible to calculate the N rate from measurements of the soil mineral N (Nmin). This method is based on a reference value (threshold) from which the Nmin measurement (the stock of mineral N present in the soil before the first N input) is subtracted. The reference value was established through field trials relating Nmin measurements to

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optimal N doses (Neeteson, 1990). Compared to the 'reference dose' method, this approach has the advantage of measuring Nmin directly and avoids having to estimate it based on reference tables. Period and depth collection of Nmin depends on the crop. However, it needs physical sampling analysis and therefore involves time, labour and financial costs.

The fertilisation recommendation guidelines are not mandatory for legal enforcement of nutrient management in Switzerland. In a legal context (to be eligible for direct payments) farms have to calculate a N (and P) balance at farm level comparing available N inputs from organic and mineral sources with average crop and forage crop demand ($N_{\text{rate std}}$) as output. Site specific corrections, long term release or additional N sources do not have to be considered.

Table 6: Correction due to the mineralisation potential, function of clay and organic matter content in Switzerland (Sinaj and Richner, 2017)

Potential of humus mineralisation	**Organic Matter (%)**			**Corrections compared to standard mineralisation (kg N ha^{-1})**
	Clay < 15%	15 to 30% clay	Clay > 30%	
Weak	< 1.2	< 1.8	< 2.5	[0 ; +40]
Standard	[1.2 ; 2.9]	[1.8 ; 3.9]	[2.5 ; 5.9]	0
Favourable	[3.0 ; 6.9]	[4.0 ; 7.9]	[6.0 ; 9.9]	[0 ; -40]
High	[7.0 ; 19.9]	[8.0 ; 19.9]	[10.0 ; 19.9]	[-40 ; -80]
Very high	≥ 20	≥ 20	≥ 20	[-80 ; -120]

3.1.4. Belgium

Belgian rules of N management are derived from two distinct documents. The first one consists of general advice on good agricultural practices, especially with the use of manure (e.g. 'Sustainable Programme of Nitrogen Management in the Walloon region', Table 1). The other one ('ASBL REQUASUD') provides the fertilisation recommendation values. It is only available for the soil analysis laboratories; no public brochure exists. Values are calculated from a model inspired from the French mass balance method (Azobil, Abras *et al.,* 2012) and parameterised separately for each of the two Belgian regions. The model is considered to be particularly efficient in calculating the mineralisation of humus. In short, as for the French method, the recommendations are mainly based on soil types, crop uptake, mineral N at sowing, humus mineralisation, direct and long-term effect of manures, effect of intermediate

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crops, effect of residues of previous crops and uses spring soil analyses to determine the initial Nmin in the soil (Eqn. 4, Table 4):

$$N_{rate} = (C_{end} + S_{end}) - (C_{Start} + S_{start} + M1 + M_{n-1} + Hu + Past + CR + IC) \quad \text{Eqn 4}$$

Explanation of symbols are given in Table 4. The specifics for Belgium are:

- The soil mineral N at harvest (S_{end}), although vulnerable to climatic impacts, is generally considered equal to 20 kg N ha^{-1} for simplicity;
- The mineral N released from ley ploughing (Past) includes alfalfa long term effects.

It is worth underlining that the measurement of mineral N at harvest is used by state authorities to control the potentially leaching quantity of N during winter, in comparison with regional references. Samples are collected between the 15th October and 30th November, to a depth of 0-90 cm for annual crops. It is therefore considered as an indicator of the fertilisation requirements at field scale. In other words, sanctions are taken according to a field indicator, and not based on the advice received by the farmer a few months before (means objectives).

3.1.5. Germany.

The German method is documented in the federal government's fertilisation ordinance that has been agreed upon by all federal states (Table 1). It consists of attributing to a given crop a standard recommended dose ($N_{rate\ std}$), and then deducing some sources of N or reasons for a higher or lower demand (AdY; Eqn 5). The standard recommended yield references and doses are derived from experiments conducted in all federal states for generating the respective crop response curves. The general approach can be presented by the following equation:

$$N_{rate} = N_{rate\,stdt} - (AdY + S_{start} + Hu + CR + IC + M_1 + M_{n-1}) \quad \text{Eqn 5}$$

Explanation of symbols is given in Table 4. The specifics for Germany are:

- The optimum yields considered in the equation are 8 t ha^{-1}, 7 t ha^{-1}, 9 t ha^{-1} for wheat, barley and maize, respectively, taken as examples. When higher or lower 5-yr average yields have been documented, additions or deductions may or must (deductions) be applied.
- 10% of the total N brought by farmyard manures is considered to provide an input to the crop the year following its spreading. So for a given year, in addition to the standard 'direct effect' corresponding to the N provided the year n, 10% of the farmyard manure-N of the previous year must be accounted for (n-1).

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- Soil analysis in spring (Feb./Mar.) is compulsory in 0-90 cm soil depth to derive S_{start} each year. In case these analyses cannot be done, S_{start} data published each spring by the regional authorities are to be considered. For certain vegetables, S_{start} is analysed on more shallow soil layers only.
- For wheat, $N_{rate\ stdt}$ varies according to quality classes (varieties with different grain protein).

In parallel to all calculations on permissible fertiliser dressings to their crops, farmers have to perform a second type of accounting: they have to report all purchases, imports and exports of nitrogen-containing products to their farm including, for example, the N content of the feed for animals, which is not included within the field-scale approach. This two-step control is particularly justified in regions with livestock, which may be impacted by high amounts of nitrogen-containing goods on their farm (e.g. Lower Saxony). The maximum of this farm-scale balance is currently 170 kg ha^{-1} and is planned to be lowered over the next years (German Federal Parliament, 2021). This second approach may be more limiting to farmers than the field-scale crop approach.

3.1.6. United Kingdom

The calculation of N rate recommendations is accurately described in a national guide ('Nutrient Management Guide, RB209', AHDB 2021) with two main brochures used in this study, the 'Section 1: Principles of Nutrient Management and Fertiliser Use' and the 'Section 4: Arable crops'. The UK system defines the crop nitrogen requirement as the amount of nitrogen that should be applied to give an on-farm economic optimum yield. Fertilisation recommendations consider all supplies and losses of N and the efficiency of N use by the crop, although the calculation does not rely on a classic mass balance equation.

The basis of the rationale consists of evaluating the 'Soil Nitrogen Supply' (SNS) which defines the amount of N (kg ha^{-1}) available for uptake from the soil, taking into account N losses but excluding external N applications. The SNS encompasses three additive separate components:

- Soil Mineral Nitrogen (S_{start}) within the normal maximum rooting depth of the crop.
- Estimate of nitrogen already in the crop (C_{start}).
- Estimate of mineralisable soil nitrogen, accounting for nitrogen which becomes available for crop uptake from mineralisation of soil organic matter (Hu) and crop residues (CR).

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In most situations, the SNS Index is identified using the Field Assessment Method, which is based on field-specific information for previous cropping, previous fertiliser and manure use, soil type and winter rainfall. The SNS Index, which is divided into seven categories, is read from tables and there is no requirement for soil sampling or analysis (Table 7). Alternatively, direct measurement (S_{start}, soil organic matter content) could be advised where organic manures have been used regularly in recent years. Whatever the method of estimating SNS, suggested values of doses are defined from experimental datasets including over 1600 N response curves (Clarke *et al.,* 2016).

Table 7: Nitrogen recommendations in UK for wheat and triticale (RB209, 2021) before the application of the efficiency coefficient

Soil category	**SNS Index**						
	0	**1**	**2**	**3**	**4**	**5**	**6**
	kg N ha^{-1}						
Light sand	180	150	120	90	60	[0;60]	[0;40]
Shallow	280	240	210	180	140	80	[0;40]
Medium	250	220	190	160	120	60	[0;40]
Deep clay	250	220	190	160	120	60	[0;40]
Deep silt	240	210	170	130	100	40	[0;40]
Organic	–	–	–	120	80	[40;80]	[0;40]
Peat	–	–	–	–	–	[0;40]	

SNS: Soil National Supply

Thereafter, the efficiency of uptake by both soil-derived N and fertiliser N is considered, taking into account soil type, crop disease, poor soil conditions, drought or other growth-inhibiting problems that will hamper the uptake efficiency of the soil mineral concentrations. Uptake efficiency (comparable to the Apparent Use Coefficient) ranges from 60 to 70%, for winter cereals fed with ammonium nitrate. Eventually, an assessment of the marginal economic response is factored into the recommended rate.

In Nitrate Vulnerable Zones within the UK, regulations are enforced in order to meet legal and environmental obligations, and place an N-max limit from manufactured fertiliser and

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organic manures that can be applied each year. In these circumstances, the N rates are generally capped at 170 kg N ha^{-1} yr^{-1}. Factors that determine the N-max limit include crop type, expected crop yields and time of year sown.

3.1.7. Spain

In the Spanish system, general recommendations are produced at the scale of the country ('Guide for rational fertilisation practices for crops in Spain', Table 1). The guide is split into two volumes: a first section with general rules and guide for nutrients, including N; the second one deals with specific crops (e.g. cereal, horticultural crops) and ends with a section on fertiliser legislation. However, the information provided is not precise enough to allow practical calculations. Therefore, each region publishes an application of these rules in the form of brochures or just on their website to fit with their specific conditions. A new decree promoting sustainable fertilisation has been published in December 2022 with local specific recommendations for regional governments.

The calculation of N recommended rates is based on a mass balance to be performed at the field scale. Recently, a decision support system was developed to help farmers and agronomists calculate nutrient requirements for a crop rotation designed by the user by picking from 149 crops (Villalobos *et al.,* 2020). This application, called 'FertiliCalc', calculates the N rates for the selected crops and allows the user to choose from a combination of straight and complex mineral fertilisers and organic compounds. The general equation (adapted from Villalobos *et al.,* 2020) can be written as:

$$N_{rate} = [(S_{end} + C_{end}) - (S_{start} + CR + A + L + Ir + M1)] / AUC \qquad \text{Eqn 6}$$

Explanation of symbols are given in Table 4. The specifics for Spain are:

- The final soil inorganic N (residual N, S_{end}), assumes a fixed value of 10 kg N ha^{-1};
- the initial soil inorganic N (S_{start}) is not introduced in the program but the user corrects by the value obtained from analysis or local information;
- the N provided by the previous crop residues is calculated very precisely, including root/shoot ratios, proportion of residues left on the field, percentage of mineralisation (generally 0.9);
- the model assumes that the soil stable organic matter is in steady state, therefore Hu = 0 and the N supply by the soil corresponds to CR and depends on the crop rotation designed;

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- atmospheric inputs account for atmospheric deposition, estimated at 10 kg N ha^{-1};
- the suggested Apparent Use Coefficient is 0.7. This relatively low value may be explained by the fact that the model does not calculate N losses mechanistically but applies coefficients based on scientific literature (Delgado *et al.,* 2008). It depends on management practices to estimate, first, N volatilisation, and then denitrification. Nitrate leaching is estimated by applying a coefficient to the remaining soil nitrate susceptible to leaching. Losses might rise up to 60% of the applied fertiliser under non-favourable conditions for high N use efficiency (Quemada *et al.,* 2016a, b).

From a regulation point of view, farmers have to write down the N application dose in the farm logbook and prove that the calculations are based on the recommended equations, but there is not an actual regulatory control on the dose itself.

3.1.8. The Netherlands

The N fertilisation recommendations in The Netherlands are based on numerous N fertilisation field experiments and are defined by committees consisting of scientists and representatives of farmers unions. These N fertilisation recommendation indicate the economic optimal N input (combination of N from animal manure and synthetic fertilisers, and corrected for the inputs from soil and crop residues). There are two committees, one for grassland and forage crops (https://www.bemestingsadvies.nl) and one for arable and vegetable crops (https://www.handboekbodemenbemesting.nl). Recommendations are explained in detail on the websites of the committees. For grassland, they depend on soil type, the total N content in the topsoil and on the frequency of grazing. Recommendations for arable and vegetable crops depend on crop type (and sometimes also variety), soil type, and the amount of soil mineral N in the top 30 to 60 cm of the soil (Table 8). They include advice on split application, described for several crops, and provide proposals of inputs for the first, second and possible third application. Moreover, the use of N mass balances is advised. The analysis of mineral N in soils in spring is not compulsory.

In terms of the calculation of the economically optimal N dose, there are mandatory soil and crop-specific N application limits (including N from manure and fertilisers) so as to guarantee that the nitrate concentration in the shallow groundwater does not exceed 50 mg NO_3^- L^{-1}. The N application limits are presented on the website of the governmental organisation RVO (https://www.rvo.nl/onderwerpen/mest/tabellen). Farmers have to comply with the N (and P) application limits, which are up to 20% below the economic optimal N application rates (depending on crop and region). Thus, all farms have to submit the N (and P) crop and soil type specific fertilization plans to RVO before the start of the growing seasons, which is then verified by RVO officials on the basis of farm-specific manure production accounts and invoices of fertiliser purchases. In specific cases, farms are visited by inspectors from the Food and Consumer Product Safety Authority (NVWA).

Table 8: Summary of N fertilisation recommendations for some crops grown in the Netherlands. N_{min} stands for soil mineral Nitrogen (Sources: https://www.handboekbodemenbemesting.nl)

Crop	Soil type	Recommended amounts
Potato (consumption)	Clay / Loess	285 - 1.1 N_{min} (0-60 cm)
Potato (consumption)	Sand	300 - 1.8 N_{min}(0-30 cm)
Potato (starch)	Sand	275 - 1.8 N_{min}(0-30 cm)
Wheat (winter)	Clay / Loess / Sand	140 - N_{min}(0-100 cm)
Wheat (spring)	Clay / Loess / Sand	120 - N_{min}(0-60 cm)
Barley (winter)	Clay / Sand	120 - N_{min}(0-100 cm)
Barley (winter)	Loess	100 - N_{min}(0-100 cm)
Barley (spring)	Clay / Loess	90- N_{min}(0-60 cm)
Barley (spring)	Sand	120 - N_{min}(0-60 cm)
Sugar beet	Clay / Loess / Sand	200- 1.7 N_{min}(0-60 cm)

3.1.9. Ireland

The Irish system is quite similar to the UK system and uses a 'Soil Nitrogen Index' (SNI) which is equivalent to a soil N supply. The SNI class (four classes in total) is calculated from the previous crop and soil type (Table 9). Account is also taken of previous applications of livestock manure N, the specific N requirement for a given crop and the likely crop yield. It is worth noting that, in the case of grasslands, for the purposes of checking compliance with the EU Nitrates Directive - National Action Programme regulations, it is best to calculate both the

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advised N application and the maximum N allowance on a whole farm basis. In situations where the N advised exceeds the maximum amount of N allowed, it will be necessary to adjust the N application rates in order to comply with the regulations described in the National Action Programme (S.I. 114 of 2022).

Table 9: Recommended N rates for Ireland (as available fertiliser) for wheat (kg ha^{-1}) having moderate yields or where proof of higher yields is not available (Wall and Plunkett, 2020). Yields are expressed with 15% moisture

Soil N Index	**Wheat (winter)**[1, 2] $\leq$ 9 tons ha^{-1}	**Wheat (spring)**[1, 2] $\leq$ 7.5 tons ha^{-1}
1	210	160
2	180	130
3	120	95
4	80	60

[1] Where proof of higher yields is available, an additional 20 kgN.ha^{-1} may be applied for every 1 tonne above reference.

[2] An extra 30 kg N ha^{-1} may be applied for milling wheat.

3.1.10. Luxembourg

The Luxembourg method is described in a decree ('Regulation concerning the use of nitrogenous fertilisers in agriculture', 24th Nov. 2000, with several updates, the last one on 28 February 2014). It states that 'the quantity of mineral N fertilisers spread per year and per hectare must not exceed the threshold quantities of N fertiliser, depending on the nature and yield of the crops and taking into account local specificities and agro-climatic conditions of the year'. Table 10 gives an overview of those maximum quantities. N fertilisation doses are calculated with the simplified 'standard approach' method also used in Germany and leading to the following recommended doses:

$$N_{rate} = N_{rate\,stdt} - (AdY + M_1) \qquad \text{Eqn 7}$$

Explanation of symbols are given in Table 4. The specifics for Luxembourg are:

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- The total N brought by manures is limited at parcel level to 170 kg N ha^{-1} (85 kg N ha^{-1} to legumes) and is considered only partially available to plants during the season;
- M_1 is oscillating from 15% (compost) to 60% (slurry) depending on manure type, spreading season, and crop, and considered to have no effect after the year of spreading.

Recommendations calculated by the guideline and current fertilisation amounts have to match on every agricultural parcel (100 % vulnerable area), at the risk of sanctions.

Table 10: Maximal amounts of N fertilisation permitted on crops (Annex of 11/24/2000 decree) in Luxembourg

Crop	**Standard yield** ton ha^{-1} (% moisture)	**N$_{\text{rate stdt}}$** kg N ha^{-1} yr^{-1}	**AdY** kg N δdt^{-1} ha^{-1}
Grain	5 (15)	160	2.5
Rapeseed	3 (9)	180	5.0
Legumes	5 (90)	30 (start only)	--
Potatoes	35 (85)	170	0.4
Fodder beet	90 (84)	235	0.3
Maize	15 (0)	190	1.4
Permanent grassland	9 (0)	260	2.7
Temporary grassland	11 (0)	300	3.0

AdY: adjustment for non-standard yield $N_{\text{rate std}}$: standard recommended dose

3.2. Global overview on the methods

3.2.1. Most and least used variables in the mass balances performed by the countries

The most widely used variables contributing to the calculation of the recommended nitrogen fertilisation rates were the N uptake by the crop, the N derived from manure and the N released by crop residues (Table 4, Figure 1). The least employed variables were the N atmospheric losses, the N supplied through irrigation water (recently stressed by Serra *et al.* 2023), the stock of mineral N at harvest, the N leached, the N in the crop at the start of the mass balance, and the long term effects of farm yard manure. The Apparent Use coefficient was only quoted three times, in spite of its ease of understanding and implementation. Taken all together, the combination of all the variables would account for the most complete

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equation, which is actually similar to the theoretical one suggested by the French method developed by COMIFER in its extended version (COMIFER, 1993).

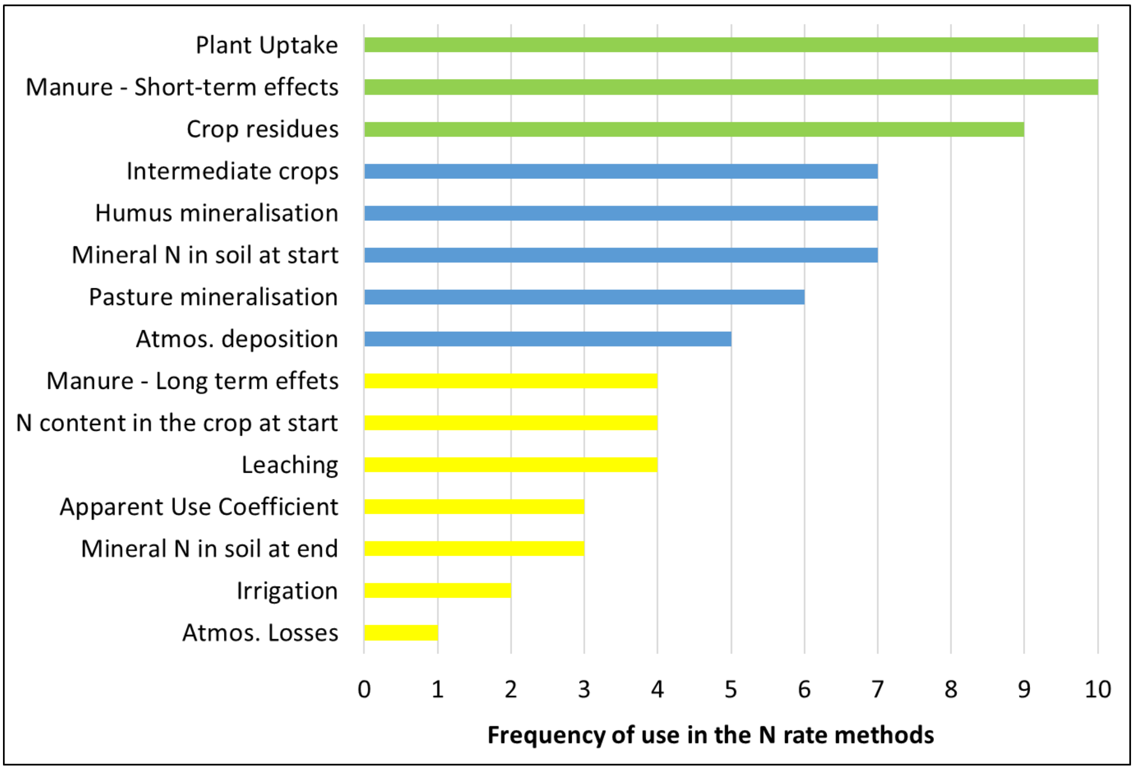

Figure 1: Decreasing frequency of the variables used in the methods of calculation of the recommended nitrogen fertilisation rates. Green: most shared variables. Yellow: least shared variables. Blue: intermediate.

3.2.2. How do countries consider the nitrogen fertiliser value of their manures?

All countries take into account the N brought by organic fertilisers (Table 4, Figure 1), whether it is through their mineral N content or/and through the mineralisation immediately following the spreading. The quantity of N available for the crop is often expressed as a percentage of the total N, which could be called ‘mineral Nitrogen fertiliser equivalent’ (Neq) or ‘Manure Nitrogen Efficiency’. This fraction varies by a 4-fold order of magnitude, from 10 to 40% (Figure 2). Besides, four countries out of 10 (Belgium, Switzerland, Germany, Italy) explicitly consider longer time effect of manure, i.e. mineral N derived from manure spread at least the year before the current calculation period.

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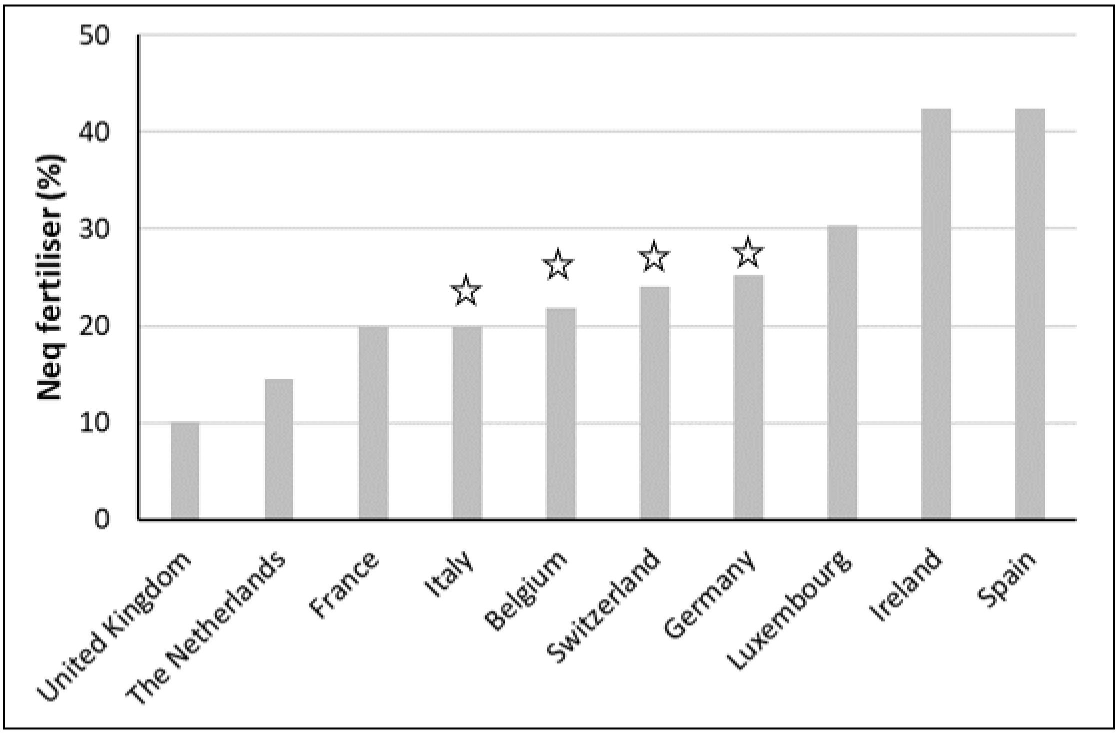

Figure 2: Percentage of N (from the farmyard manure use in the case study) considered to be available for the crop in the season after its spreading. Stars indicate the countries that take into account with a separate budget component a long-term effect (> 1 year) of previous spreading on the soil N supply

3.2.3. Regulatory status of the calculation methods.

The N fertilisation rates recommended within the ten countries have different levels of integration of nutrient management in their legal enforcement (Figure 3), from methods providing direct support for regulatory controls (Luxembourg, Ireland, the Netherlands) to those only related to bio-physical criteria (Belgium, Switzerland, Italy except for farmers voluntarily adopting Integrated Production rules).

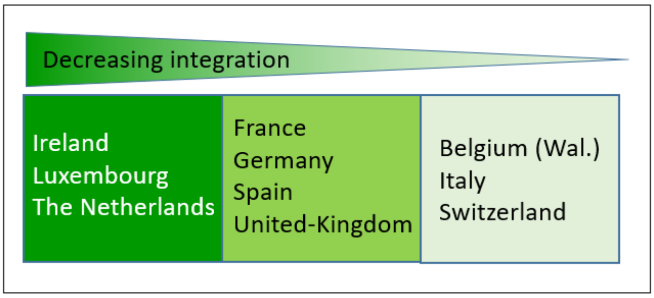

Figure 3: Countries ranked by decreasing integration of the fertiliser recommendations in their legal enforcement (from dark to clear green)

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3.3. Nitrogen recommendation rates: results of the case studies

Each of the country-specific methods of N-rate calculations were applied to two different farming systems (animal oriented farm *vs* pure crops). There were large discrepancies between the ten countries' recommended N fertilisation rates (Figure 4). In the arable farm scenario, i.e. without organic amendments, the difference in the recommended doses reached 100 kg N ha^{-1}. Values ranged from 110 kg N ha^{-1} (Belgium, Wallonia) up to 210 kg N ha^{-1} (Luxembourg). The median value was around 150 kg N ha^{-1}. Three countries gave the same amount (France, Italy and United Kingdom), with 170 kg N ha^{-1}. In the farming system including animals, the difference was slightly higher (from 15 to 135 kg N ha^{-1}). The ranking of countries varied between both scenarios, although extremes remained the same (Belgium and Luxembourg, for minimum and maximum N rates, respectively).

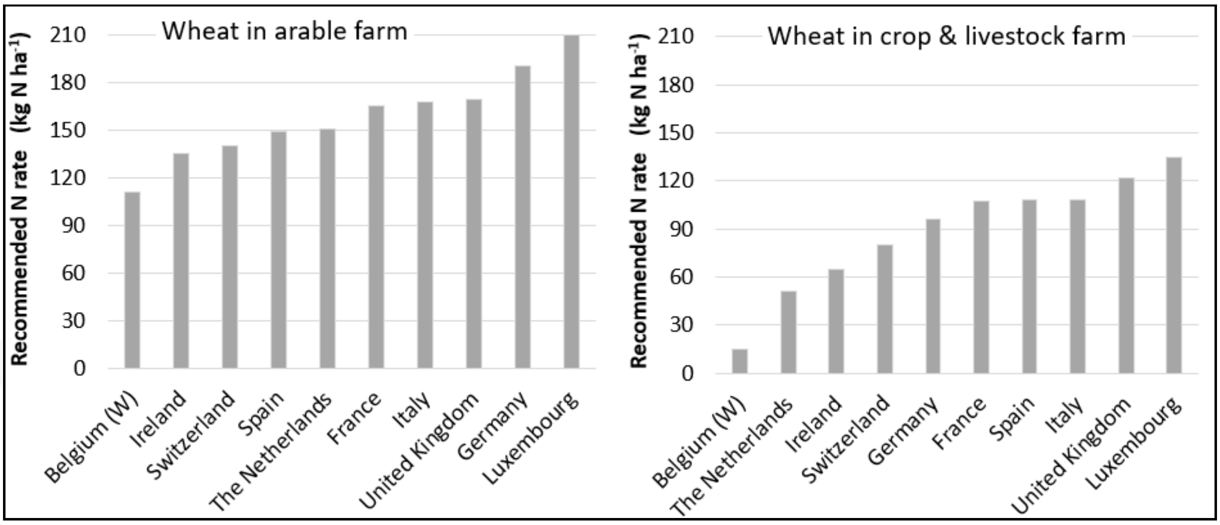

Figure 4: Recommended nitrogen (N) fertilisation rates for ten west European countries, calculated from the official national methods, and applied on a theoretical study case consisting of a wheat crop grown in two types of farming systems.

The recommendation rates gaps' can be put in relation with the three most used variables (i.e. N uptake by the crop, N derived from manure, and N released by crop residues, see chapter 3.2.1.). Table 11 summarises for each country the recommended fertilisation rates (first column) and the values of the attached key-variables. Interestingly, the recommendations rates are not correlated to any of the variables, taken alone.

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Table 11: Detail of the most shared variables within the national mass balance equations, ranked in the increasing order of N recommended rates (N_{rate}). C_{end}, M_1 and CR stand for total plant N uptake, Manure and Crop Residues contributions to plant nutrition, respectively. N.A.: non available (not explicitly calculated)

	N_{rate}	**C_{end}**	**M_1**	**CR**
Country	kg N ha^{-1}			
Belgium (W)	111	225	18	20
Ireland	135	150	35	N.A.
Switzerland	140	150	20	0
Spain	149	184	35	35
The Netherlands	151	189	12	20
France	165	210	16	20
Italy	168	210	16	20
United Kingdom	169	N.A.	8	N.A.
Germany	190	215	21	10
Luxembourg	210	210	25	-

4. Discussion

4.1. Typology of calculation methods used within the different countries

All the calculation methods are more or less comparable to a N mass balance, with some nuances, leading broadly to three categories. The first category of methods can be summarized as a 'full nitrogen mass balance' method, consisting of an additive system where mineral nitrogen outputs and inputs items of an equilibrium equation are completed at the field-scale. This first category is used by France, Italy and Spain. These three countries are among those exhibiting the highest number of variables (Table 4). Secondly, a 'corrected standards' principle, corresponding to a fixed recommended dose (also called standard fertilisation), for a given crop and in a 'standard' situation potentially corrected to take into account any gap due to environmental or agricultural practices. This second category is implemented by Germany, the Netherlands, Switzerland, Luxembourg (and Italy when the simplified standard rates are adopted instead of the full budget). Thirdly, the 'pre-

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parametrisation' calculation is similar in its logic to the 'corrected standards' but applied to several standard soil and climate situations. It relies on a Soil Nitrogen Supply typology (United Kingdom, Ireland) or on a model parameterisation (Belgium). In practice, such a three-class typology is a bit artificial as every method relies on field parameterisation or could be presented as a mass balance, before being simplified. In a earlier attempt to compare the recommendations systems for N fertilisation among some European countries, MacKenzie and Taureau (1997) suggested another classification: N-Index system (close to the current English and Irish 'Soils Nitrogen System', the 'additive method' (corresponding to our so-called 'full nitrogen mass balance'), the 'Apparent Use Coefficient method' where the additive method was not applicable, and, eventually, a 'soil mineral method', mainly based on pre-seedling soil sampling. The two typologies are close but do not entirely match, mainly because we consider the soil mineral N sampling as an optional indicator usable in each category rather than a complete recommendation method in itself.

4.2. Assessing some causes of heterogeneity of the calculated rates

We tried to relate the differences between N recommendations calculated on the two contrasted wheat crop systems to the number of variables taken into account in the algorithms (4.2.1), the weight given to the N leaching in the algorithms (4.2.2), the sensitivity of the most shared variables, i.e. contribution of N from organic amendments (4.2.3) and uptake of N from the crop (4.2.4), the uncertainties in N budget balances (4.2.5) and the regulatory status of the equation, i.e. if and how the fertiliser recommendation is used for legal enforcement of nutrient management (4.2.6).

4.2.1. Questionable benefits of using more variables

At a European scale, the complexity of fertilisation methods varies considerably (Klages *et al.* 2020), as illustrated by the huge difference in the number of variables involved in the calculations (Table 4). However, our study revealed that the number of variables explicitly used by each country was not directly related to the recommended N fertilisation rate (Figure 5). The country exhibiting the highest complexity (France) displayed intermediate N-rate values, and did not necessarily correlate with dose of N recommended. With only three variables taken into account, Luxembourg's calculations led to the highest N recommendation. Indeed, in this case study, the 'real value' corresponding to optimum N fertilisation rate in each country or region will always remain unknown.

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From a practical point of view, methods relying on mass balances are more complicated to implement. The corrected standards methods are the easiest to apply in practice, because farmers can simply read the optimal N applications from published tables for each crop type (and sometimes variety) and soil type. A pre-parameterised calculation exhibits intermediate difficulties in practice. On average, methods relying on mass balances required the highest number of variables (e.g. France and Italy, 10 variables, Table 4). Corrected standard and pre-parameterised methods included a range of 6 to 9 variables except for Luxembourg (3). Including a lower number of variables does not necessarily mean that some mechanisms are totally ignored or neglected. Sometimes, they are (e.g. atmospheric deposition in UK, N in irrigation in Ireland), but they may be integrated or pooled with other more integrative variables such as the long term N supply from fertilisers, which are accounted for by the measurement of soil mineral nitrogen at seeding in France. By the same logic, the quantities of N leached during winter are also indirectly included in the estimation or measurement of the residual soil mineral N after winter. It is also the role of the 'Apparent Use Coefficient', standing for a 'security factor', to pool effects of N losses, which are difficult to measure or even estimate (N leaching, atmospheric losses, etc.).

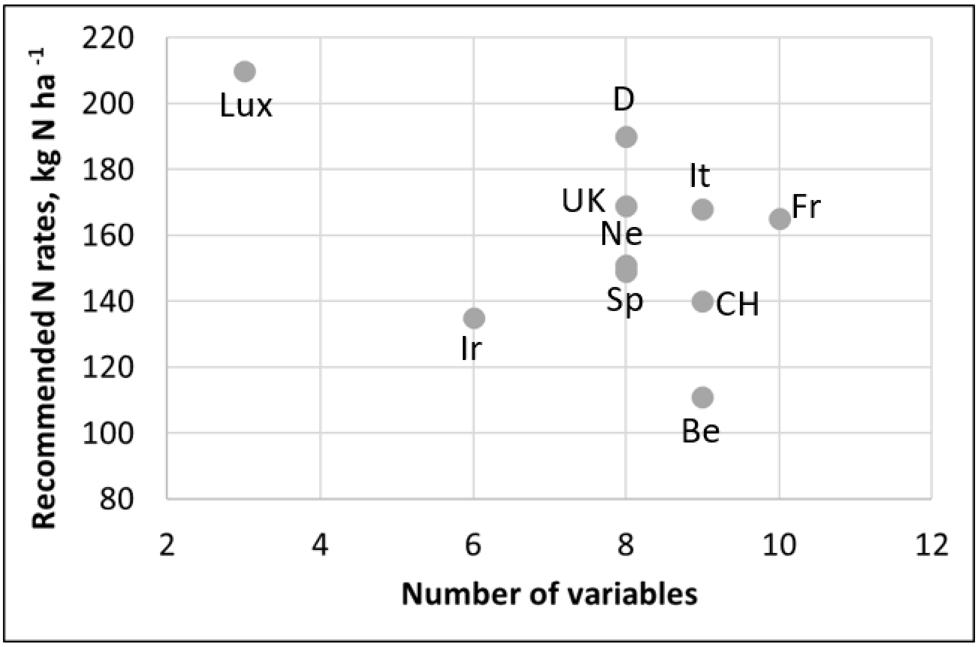

Figure 5: Relationship between the recommended N fertilisation rates (arable scenario) and the number of variables explicitly present in the fertilisation calculation methods. Belgium (Be), Germany (D), France (Fr), Ireland (Ir), Italy (It), Luxembourg (Lux), the Netherlands (Ne), Spain (Sp), Switzerland (CH) and United Kingdom (UK).

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4.2.2. Variable impact of using an explicit parameter for leaching.

We analysed the effect of the presence of the 'leaching' variable in the equations (Table 4) on the final N recommendation rate (Spain, UK, Switzerland and Italy), with the hypothesis that calculating N leaching explicitly would result in a higher N fertilisation rate, on average. In reality, such a trend did not occur (Figure 4). By comparison, when the equations neither refer to leaching nor use any apparent use coefficient (or security factor) (Belgium, Ireland, Luxembourg, The Netherlands, Table 4), one could expect an underestimation of the outputs, which would in turn lead to recommend low values. Again, such a conclusion cannot be deduced from the results. As only one rainfall scenario was tested (400 mm between the 1st of October and the 1st of March), one should consider our conclusions with caution as there can be some threshold effects. For example, in UK (AHDB 2020), there are two categories of winter rainfalls (normal or high), leading to move the Soil Nitrogen Supply values from one category to the very next one. In Switzerland (Sinaj and Richner 2017), winter rainfall amounts are split between low, normal and high amounts (<60 mm month^{-1}, [60-80mm month^{-1}] and > 90 mm month^{-1}, respectively). It is the same principle for Italy (Ammassari P., 2020) but based on cumulated winter rainfalls, between October and January (<150 mm, [150-250mm month^{-1}] and > 250 mm). These rainfall-based classes stand for approximate estimators of the real N lixiviation. Indeed, modelling N leaching is a very complex step (Addiscott 1996), and can hardly be performed for sandy soil, even at field-scale.

4.2.3. Manure Nitrogen consideration is different

The value gaps between the manure nitrogen efficiencies of each country (Figure 2) significantly account for the differences in the recommended fertilisation rates of the livestock farm scenario (Figure 4). For example, bringing a total of 83 kg N ha^{-1} (the case study) will only supply the following wheat crop with 8 kg N ha^{-1} in UK, whereas this amount is considered to be 35 kg N ha^{-1} in Spain. The Neq values obtained in our study and their range match with those collected by Webb *et al* (2013) in 20 European countries for solid cattle manure (5-60%). These discrepancies may be due to the growing conditions prevailing during manure spreading (e.g. lower mineralisation in colder and dryer climates). This interferes with the spreading authorisation periods, which are country-specific. For example, high percentages may correspond to storing the manure and applying it in spring under more favourable conditions. Besides, the differences may reflect average animal housing and feeding, storage capacities... Finally, these percentages are mostly not linked to possible long-term release effects (Figure 2). These differences in N supply from organic amendments explain why there are much greater differences in the recommended dose when fertilisation relies on organic rather than on mineral fertilisation (Figure 4).

4.2.4. Variations in the assumed level of nitrogen uptake by crops

The estimate of crop N uptake (not only in grains but entire shoots) varies from country to country, even with the same target yield (Table 11). The 70 kg N ha^{-1} gap between Switzerland and Ireland, on one side (150 kg N ha^{-1}), and Germany and Belgium on the other side (220 kg N ha^{-1}), is a supplementary cause of heterogeneity of the N fertiliser recommendations underlined on the Figure 4. One explanation is that the N uptake may include more or less secondary factors (e.g. uptake efficiency) which are not explicit in the equations (D. Wall, oral com., for Ireland). Pan *et al.* (2006) showed that water and temperature conditions during wheat growth were strong determinants of N uptake and eventually N nitrogen content. Alternatively, the difference could partially be accounted for by the abilities of varieties to concentrate more or less the N in their grains (Sieling and Kage 2021). For example, the N uptake of wheat grown for animals feeding is about 20% lower than for flourmill (COMIFER 1993). The United Kingdom value could not be found as it is merged with other variables underlying the Soil Nitrogen Supply calculation.

In a general way, the 'N uptake by crop' variable largely relies on 'target yields'. This last variable, apparently easy to set, is, however, regarded as one of the weakest point of the mass balance methods because it is considered regularly overestimated (Ravier *et al.* 2016, Ransom *et al.* 2020). These authors think that the difficulty in estimating the appropriate yield is one of the main cause of uncertainty of the N mass balance method, and, hence, of the high N losses.

4.2.5. Uncertainties in N mass balances

Ideally, each dose should be accompanied by a margin of error, which was however impossible to estimate in the context of this exercise where single rates only could be calculated for each scenario. By using Mote-Carlo simulations, Oenema *et al.* (2003) estimated a relative uncertainty (coefficient of variation) ranging from 11% for crop uptake and denitrification in soil, to 15% for ammonia volatilization, 26% for leaching to groundwater, and 47% for leaching to surface waters. At the scale of the whole mass balance

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itself, an order of magnitude of 45 kg N.ha^{-1} for uncertainties was suggested by preliminary results of an ongoing French study (Degan, Personal Communication). Therefore, these results indicate that the discrepancies obtained (Figure 4) could be considered as significant, at least for the extremes.

4.2.6. Impact of the regulatory status of the calculation methods on the recommended rates

Fertilisation planning and nitrogen budgeting may be strongly influenced by their legally bound status (Klages *et al.* (2020). Our former classification (Figure 3) should, however, be taken with caution, as it interferes with the proportion of vulnerable zones in each country and the ability of some regions to handle this task. For example, in Luxembourg or Germany, 100% of the country is classified as 'Nitrate Vulnerable Zone', whereas this proportion is half in England and France. In Federal countries (e.g. Switzerland, Germany), the level of integration of nutrient management in legal enforcement may vary.

Countries whose calculation methods exhibit a high level of legal enforcement (e.g. Luxembourg, Figure 3) have a slight tendency to recommend the higher rates of N, whereas where the dose is smaller, there is a weak legal enforcement (potentially leading to overcharging). One explanation is that higher compulsory upper limits might be more acceptable within farmers communities and associations, with a lower feeling of risk on yield compared to lower advised doses. This argumentation should probably be confirmed by social and political sciences.

4.3. Best innovations among the ten investigated countries

It is obvious that the different methods basically rely on the same concepts, i.e. estimations with more or fewer calculation steps of the N mass balance centred at crop and year scale. However, among the ten countries, two exhibit original tools that we consider (in our opinion) worth highlighting.

In Germany and Switzerland, the supplementary mandatory mass balance performed at the farm level is a promising tool wherever massive imports of N-enriched feed is a potential threat to water and air quality (Klages *et al.* 2020). So far, the German regulation allows an excess of 170 kg N ha^{-}1 yr^{-1} per holding; this amount will be lowered in the coming years. This farm-scale mass balance is considered to be a safeguard against risks of fraud or

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permissive field mass balance parameterisation. United Kingdom exhibits the same threshold at farm scale, but only for organic inputs.

Belgium is the only country implementing a control on the residual soil mineral N (RSMN) at harvest. Although the measurement of such an indicator probably exhibits methodological issues, its main quality is to be closely linked to the risk of leaching during the critical period of autumn and winter rainfalls. RSMN measurements are already suggested to farmers in other countries (France, Luxembourg) for informative purpose and without any relation to control, so far. RSMN with legal enforcement or for result based payments are now implemented in the 2023-2027 Strategic Plan of CAP (European Commission, 2023). D'Haene *et al.* (2014) already pointed out that the RSMN could serve as an 'indication of the efficiency of the applied effective N and could be used as a basis for a rational N fertilisation advice and maximum allowed N fertilisation rates'.

5. Conclusions

This study compared the methods used by ten West European countries to calculate the Nitrogen fertilisation rates recommended for farmers. These quantities are of particular importance regarding the impact on the air and water environments of the reactive forms of nitrogen, and the relationship to the financial sustainability of farms in the current inflationary context. Our stocktake approach was particularly aimed at understanding the underlying principles, the commonalities and differences of each method (i.e. type of equation), and, above all, at highlighting innovations, i.e. promising approaches that could increase the nitrogen use efficiency of fertilisers.

Our study shows that the nitrogen field-scale mass balance approach can be considered as universally used in every country, with, however, large discrepancies in the number of parameters and various use of modelling or field network to edit references. In some countries, different parameters may be combined, giving the impression that some methods are 'simpler' than others. However, we underlined that there was no relationship between the number of parameters in an equation and the recommended N rate for two distinct cropping scenarios.

According to the information provided by this study, we suggest that any attempt to standardise the fertilisation rules would meet the following limits:

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a) there is great heterogeneity on variables that would a priori be considered to be robust and standardised (N uptake by plants, N released from farmyard manure);

b) some methods directly meet regulatory requirements, while others are centred on technical and economic issues;

c) the estimation of N losses, either by denitrification/volatilisation or by leaching, are generally addressed by ‘security factors’, hidden in integrative factors or apparently neglected. As they determine the gross nitrogen use efficiency, we suggest that the most exacting rule apply to all countries;

d) in spite of apparent homogeneity of calculation at the country scale, most of the countries exhibit regional adaptations to local specifics; therefore, the real picture of heterogeneity is likely larger than the one depicted in this study.

Standardisation of the method should not be an end in itself; it should only serve to improve nitrogen use efficiency at the local, regional and finally European scale. There is a real risk that efforts made by countries to adopt the same method would be meaningless on international level. This European nutrient recommendation systems stocktake study indicates that investment in initiatives that promote increased N efficiency (field + farm mass balances, fine soil organic matter mineralisation calculation, decision-making tools such as soil nitrate tests, canopy reflectance sensing) may be an appropriate strategy for achieving agronomic and environmental targets on farms into the future.

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