Stocktake study of current fertilisation recommendations across Europe and discussion towards a more harmonised approach

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Abstract

The European Commission has set targets for a reduction in nutrient losses by at least 50% and a reduction in fertiliser use by at least 20% by 2030 while ensuring no deterioration in soil fertility. Within the mandate of the European Joint Programme EJP Soil 'Towards climate-smart sustainable management of agricultural soils', the objective of this study was to assess current fertilisation practices across Europe and discuss the potential for harmonisation of fertilisation methodologies as a strategy to reduce nutrient loss and overall fertiliser use. A stocktake study of current methods of delivering fertilisation advice took place across 23 European countries. The stocktake was in the form of a questionnaire, comprising 46 questions. Information was gathered on a large range of factors, including soil analysis methods, along with soil, crop and climatic factors taken into consideration within fertilisation calculations.

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The questionnaire was completed by experts, who are involved in compiling fertilisation recommendations within their country. Substantial differences exist in the content, format and delivery of fertilisation guidelines across Europe. The barriers, constraints and potential benefits of a harmonised approach to fertilisation across Europe are discussed. The general consensus from all participating countries was that harmonisation of fertilisation guidelines should be increased, but it was unclear in what format this could be achieved. Shared learning in the delivery and format of fertilisation guidelines and mechanisms to adhere to environmental legislation were viewed as being beneficial. However, it would be very difficult, if not impossible, to harmonise all soil test data and fertilisation methodologies at EU level due to diverse soil types and agro-ecosystem influences. Nevertheless, increased future collaboration, especially between neighbouring countries within the same environmental zone, was seen as potentially very beneficial. This study is unique in providing current detail on fertilisation practices across European countries in a side-by-side comparison. The gathered data can provide a baseline for the development of scientifically based EU policy targets for nutrient loss and soil fertility evaluation.

KEYWORDS
fertilisation, fertilisation recommendations, nutrient management, nutrient use efficiency, precision agriculture

1 | INTRODUCTION

Appropriate fertilisation practices will help optimise plant nutrient uptake and crop production, supporting a growing global population. At the same time, this should meet environmental legislation associated with the EU Nitrates Directive (91/676/EEC) and the EU Water Framework Directive (2000/60/EC) and targets underpinning the European Green Deal (COM/2019 640 final) in particular (Hirte et al., 2021; Klages et al., 2020). Indeed, in many countries, fertiliser recommendations are now capped by nitrogen (N) and phosphorus (P) application standards (maximum allowable amounts), but nutrient emissions from agriculture need to be lowered further. The EU Commission aims to reduce nutrient losses by at least 50% and reduce fertiliser use by at least 20% by 2030, while ensuring that there is no deterioration in soil fertility (COM/2019 640 final). The European Green Deal (https://ec.europa.eu; COM, 2019 640 final) aims to transform the EU into a modern, resource-efficient and competitive economy with no net emissions of greenhouse gases by 2050, along with a Soils Strategy (https://ec.europa.eu/environment/publications/eu-soil-strategy-2030_en) to restore soils and make them more resilient, food more healthy and affordable and to foster fresh air, clean water, healthy soil and biodiversity. To achieve this, it is essential that we become more efficient, resourceful and aware of how we are managing our landscape. Much can be learned from questioning current practice and looking for alternatives, solutions and learning from others.

Highlights

- A stocktake study assessed fertilisation guidelines and practices across 23 European countries.
- Fertilisation guidelines vary between neighbouring countries, even within the same environmental zone.
- Agro-ecosystem differences across Europe present barriers to harmonisation of fertilisation practice.
- Shared learning and a collective approach to tackling environmental targets were viewed as beneficial.

Fertiliser recommendations and advice to farmers are primarily based on agronomic requirements, specific to soil and crop type and generated individually within each country. The general common principle is to reach or maintain target ranges of plant available nutrients in soil (phosphorus (P), potassium (K) and magnesium (Mg) specifically; Steinfurth et al., 2022; Mattila & Rajala, 2022; Zbíral, 2016). It has been recognised for many years that there are a number of different soil test methods available. More than one soil test for specific nutrients frequently operates within a single country, and between neighbouring countries, with several published research articles detailing differences in soil P tests in particular (Mattila & Rajala, 2022; Neyroud & Lischer, 2003; Steinfurth et al., 2022; Vero et al., 2021). There have been far fewer published comparisons of methodologies for assessing other plant available nutrients and trace elements between countries in Europe. There are also different methods of calculating fertilisation requirements (Kuchenbuch & Buczko, 2011; Tóth et al., 2014) and considerable differences in fertiliser recommendations across different countries exist, especially for N and P (Jordan-Meille et al., 2012; ten Berge & van Dijk, 2009), even with similar soil types and within the same environmental zone. Again, there are few published comparisons of fertiliser recommendation calculations for a wide range of plant available nutrients and trace elements.

Along with differences in fertilisation recommendations, EU member states also tend to follow different approaches to tackling nutrient loss, particularly N loss and N use efficiency (Klages et al., 2020). Policy measures relating to manure production per hectare, and to the use of stabilised manures and other exogenous organic matter additions (such as sewage sludge), are viewed as being very successful at reducing emissions (ten Berge & van Dijk, 2009; Vrebos et al., 2017) but further measures are required. Crops are often fertilised above recommended levels to avoid the risk of yield loss (Steinfurth et al., 2022). However, improving fertilisation techniques to better match nutrient requirements with crop demand would improve overall nutrient use efficiency, particularly N use efficiency (Argento et al., 2022; Higgins et al., 2019).

Where different soil tests and fertilisation guidelines operate within close proximity to one another in neighbouring countries or regions, these differences can potentially contribute to a number of issues. A specific example of this is where countries are separated by a land border (Vero et al., 2021). Confusion or uncertainties among farmers living in border areas can arise if there is conflicting advice operating within close proximity. It can also generate issues where there are management requirements and legislation to reduce nutrient losses (N & P) to rivers, lakes or other inland waterbodies within cross-border catchments. Vero et al. (2021) highlighted how managing nutrient loss from agriculture in a scenario such as this can be problematic and requires cooperation and understanding from authorities on both sides of the border. Transboundary air pollution, such as ammonia and nitrous oxide emissions from agriculture and their impact on biodiversity and amenity value of natural capital, also requires consideration.

The overall objective of this study was to assess the current status of fertilisation recommendations across Europe and the potential for harmonising methods used for generating fertilisation guidelines between neighbouring countries and across regions. This survey contributed to the creation of a research roadmap towards climate-smart sustainable management of agricultural soils, as part of EJP SOIL, a European Joint Programme project under the EU's Horizon 2020 Research and Innovation Programme (https://ejpsoil.eu/). The aim of the synthesis was to collect systematic information from all participating countries on current fertilisation guidelines, how these are generated and managed, along with methods of communication and dissemination. There were six main objectives of this study:

- *Objective 1*: To complete a stocktake of current fertilisation guidelines across a number of European countries.
- *Objective 2*: To identify the key variables influencing fertilisation guidelines, for example, climate, soil properties, cropping system, nutrient loss and provide details on soil test methods used for P, K, Mg, Ca along with C and N.
- *Objective 3*: To identify synergies, similarities and differences in fertilisation guidelines between neighbouring countries.
- *Objective 4*: To assess the potential for the harmonisation of methodologies and barriers to harmonisation.
- *Objective 5*: To identify the stakeholders involved in formulating fertilisation guidelines within individual countries.
- *Objective 6*: To evaluate the importance of knowledge transfer and community engagement.

2 | MATERIALS AND METHODS

A questionnaire was compiled and distributed in 2020 among the 26 European partners within the EJP Soil programme. Prior to circulation, the questionnaire was disseminated via a webinar attended by 90 members of the EJP Soil consortium across Europe. The webinar detailed the content and structure of the questionnaire and was an opportunity for review and feedback on the questionnaire format. It was recommended that the questionnaire should be completed by a person or team within each country with responsibility for or involvement in the compilation and dissemination of current fertilisation guidelines within their region. They should therefore be regarded as a national expert in terms of the detail provided. In most cases, the questionnaire was completed with assistance from more than one person per country, as required. It was the responsibility of the personnel within each country to appoint the appropriate experts and gather the necessary information. The experts who contributed the information for the stocktakes are all co-authors within this manuscript. The questionnaire was categorised into the six main objectives, with a series of questions addressing each objective. Under each objective, there were a number of questions, which are detailed in Appendix 1. Participants had 6 months to return their completed questionnaire.

Responses were received from 24 of the 26 project partners within EJP Soil (Austria, Belgium [Flanders], Belgium [Wallonia], Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom). Participants were asked to identify what environmental zones (ENZ) of Europe their country were located in. Where submitted information required further detail or clarification, this was obtained through follow-up conversations. For example, the level of detail provided on crops and soil types varied between countries, and clarification was sought where necessary. A hybrid workshop was held in December 2022 to discuss the findings of the stocktake to which all of the fertilisation experts were invited. The results presented below reflect the questionnaire responses, interpreted in this manuscript to the best of the authors' abilities. Across the six objectives, a total of 46 questions were answered by each responding country. This generated a large overview of how fertilisation guidelines are currently formulated and delivered to stakeholders within each individual country. Responses to individual questions were standardised through tables and charts to make comparisons between countries.

If participants had recorded no information to a specific question, their response was either recorded as such or further information acquired through follow-up contact and discussions, depending on the question. Due to the nature and extent of the data gathered through the questionnaire, advanced statistics were not appropriate. The large number of questions asked and the varying detail of the answers were unique, and commonly used statistical approaches, such as the Likert scale, would not have enabled the necessary data to be captured. Instead, answers to each individual question were handled independently and compared across the 23 European countries.

3 | RESULTS

3.1 | Objectives 1 and 5

3.1.1 | Frequency of updates to fertilisation guidelines across a number of European countries

Each of the 24 project partners surveyed (Austria, Belgium [Flanders], Belgium [Wallonia], Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom) has its own specific fertilisation guidelines. The frequency of updates to fertilisation guidelines varies significantly between countries. In one third of the countries surveyed, fertilisation recommendations are updated infrequently (over 10 years between updates [Estonia, Latvia, Lithuania, Portugal, Slovakia, Spain and Hungary]; Figure 1). Germany, Norway, Slovenia and Turkey reported that fertiliser recommendations are updated approximately every 10 years. Small, regular updates to some nutrients, in response to new scientific data or agronomic trials, occur in France, the United Kingdom, Netherlands, Austria, Italy, Poland and Sweden. This would mainly be for individual crops such as cereals or oilseed rape. In other countries (Belgium [Flanders], Belgium [Wallonia], Denmark, Finland and Ireland), updates, mainly to N and P advice, occur on a 3- to 5-year cycle, but other nutrients are updated less frequently (Figure 1).

3.1.2 | Identification of stakeholders involved in formulating fertilisation guidelines

In all countries, an advisory committee is responsible for formulating and updating fertilisation guidelines. This comprises representatives from research, economic actors, government bodies, public authorities, education and farmers organisations and involves collective decision-making. In some countries, soil laboratories and commercial fertiliser companies are also involved. The composition and number of stakeholders present on this committee vary quite widely between countries (Table 1).

3.2 | Objective 2

3.2.1 | Key variables directing fertilisation guidelines, for example, climate, soil, cropping system, nutrient loss

Environmental zones represented by countries completing the questionnaire are detailed in Figure 2.

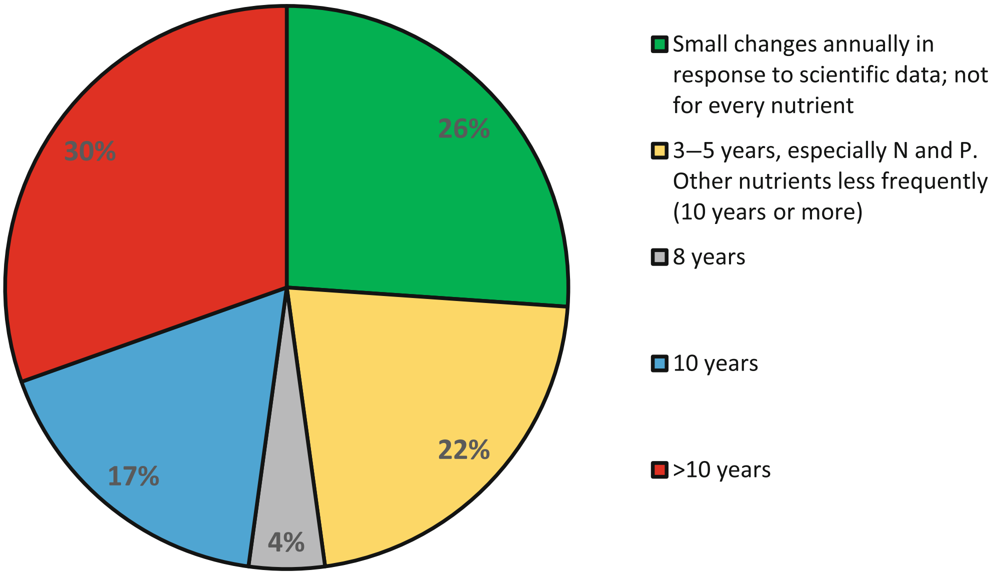

FIGURE 1 Frequency of updates to fertilisation guidelines in participating countries.

Participants stated the main crops grown in their country (Table 2), along with details of the dominant soil types. Other variances included differences in soil classification systems and the huge number of individual soil series within individual countries, which was difficult to capture in a summary table. For example, there are over 4000 soil type classifications within the Flemish region and over 700 in the United Kingdom. Ireland reported 213 different soil series.

In all European countries in this study, fertiliser recommendations are based primarily on agronomic requirement and economically optimum fertilisation rate, but also with consideration of nutrient loss and environmental impact. All (100% of) participating countries stated that the Nitrates Directive and/or Phosphorus Regulations have a strong influence on capping upper fertilisation limits. All countries reported crop-specific fertiliser guidelines. In addition, there are regional adaptions to fertilisation guidelines within individual countries, relating to a number of factors. In total, 20 out of 24 regions reported differences in fertiliser recommendations depending on soil properties, in particular soil texture and climatic attributes (e.g., rainfall totals). Other important factors taken into consideration, and which varied by individual countries and regionally within countries, included recent fertilisation history, preceding crop and organic manure management (organic fertiliser type, manure or slurry source).

Soil pH and recommendations for liming were reported as being included alongside fertiliser guidelines in 22 countries surveyed. In Italy and Spain, there is a dominance of sub-alkaline/alkaline and calcareous soils across these countries; therefore, soil acidity and liming are of less importance. When asked about soil conditioners, all 23 countries reported that soil conditioners in the form of compost, manure, lime and digestates are used, but the definition of a soil conditioner is not clear across Europe and not uniform. 'Synthetic' soil conditioners (polymers) were not widely used. Generally, soil conditioners may be applied by individual farmers, but information is not widely included in recommendations or nutrient management advice. Advice on soil conditioners tends to be provided directly by individual companies and less at a national advisory scale across Europe.

3.2.2 | Soil extraction tests used for plant available P, K, Mg and Ca, along with soil total N and C

Soil P

Sixteen soil P tests were identified as being used within the 23 participating countries (Table 3). In some countries, more than one soil test for P is used within a single country (e.g., in the Netherlands, Switzerland, France, Poland, Portugal, Turkey and Italy). The most commonly used soil P tests across participating countries were the Olsen soil P test (sodium bicarbonate) and the Egner–Riehm method (ammonium lactate; Table 3). Other less frequently used tests include Joret-Hébert (ammonium oxalate) and Dyer tests (citric acid), mainly used in France and CO_2-saturated water method used in Switzerland.

In addition to the variation in soil P tests used, soil analysis methods for carbon (C), K, Mg, Ca and N also vary widely (Tables 4–6).

TABLE 1 Description of the main organisations involved in formulating fertiliser guidelines per participating country (in alphabetical order).

Country	Main organisations responsible for formulating fertilisation guidelines
Austria	The advisory board for soil fertility and soil protection of the Federal Ministry of Agriculture, Forestry, Regions and Water Management
Belgium (Flanders)	Flemish Government, Flemish Government Department of Agriculture and Fisheries, Flemish Government Department of Environment, Flemish Land Agency (VLM), Flemish Environment Agency (VMM), Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Consultancy Service for Better Soil and Water Quality (B3W), Boeren Bond (BB), Soil Service of Belgium (BDB) and Research and Advisory Board on Sustainable Fertilisation.
Belgium (Wallonia)	RequaSud, Laboratories du CARAH (Ath), Centre provincial de l'agriculture et de la ruralité (La Hulpe), Centre d'information Agricole de la Province du Luxembourg (Bastogne), Laboratories de l'Office agricole de la Province de Namur (Ciney), Laboratories de la province de Liège (Tinlot-Scry).
Denmark	Aarhus University, SEGES (National Agricultural Advisory Service), LBST (The Danish Agricultural Agency), Copenhagen University and the Ministry of Food, Agriculture and Fisheries of Denmark
Estonia	Centre of Estonian Rural Research and Knowledge, along with other relevant stakeholders
Finland	Ministry of Agriculture and Forestry, Luke (Natural Resources Institute Finland), Farmer's union, fertiliser companies (Yara) and regional authorities
France	French Committee for the Study and Development of Sustainable Fertilization (COMIFER), Institut National de la recherche Agronomique (INRAE)
Germany	Federal Ministry of Food and Agriculture, Federal Ministry for Environment, Nature Conservation, Nuclear Safety and Consumer Protection, Julius-Kühn Institute, Thünen Institute, Ministries at federal and state level, regional extension services
Hungary	Ministry of Agriculture, The Hungarian Chamber of Agriculture, Centre for Agricultural Research
Ireland	Teagasc, Crops, Environment and Land Use Department, Johnstown Castle (Government-funded research organisation)
Italy	Ministry of Agriculture, Food Sovereign and Forestry (MASAF) – Group of Experts of Agronomic Techniques (GTA)
Latvia	Official regulations of the Cabinet of Ministers, Republic of Latvia, Ministry of Agriculture of the Republic of Latvia in collaboration with Latvia University of Life Sciences and Technologies develop manuals with recommendations and education materials. State Plant Protection Service of the Republic of Latvia provides state supervision and official control to ensure the sustainable use, protection and monitoring of crop resources.
Lithuania	Lithuanian Research Centre for Agriculture and Forestry (LAMMC) in cooperation with Lithuanian Advisory Service in the order of Ministry of Agriculture. The newest recommendation provided in the Code for Good Agricultural Practices.
Netherlands	There are standing committees that develop the fertilisation guidelines specific for grassland and fodder crops and specific for arable crops and vegetables. These committees consist of researchers, independent advisors, representatives of soil laboratories and farmers organisations.
Norway	Norwegian University of Life Sciences (NMBU), Norwegian Institute of Bioeconomy Research (NIBIO) and Norwegian Agricultural Extension Service (NLR)
Poland	The Institute of Soil Science and Plant Cultivation—State Research Institute (IUNG), the Institute of Technology and Life Sciences—State Research Institute (ITP), the Institute of Horticulture—National Research Institute (InHort), Ministry of Agriculture and Rural Development, National Agrochemical Station (KSChR).
Portugal	National Institute for Agrarian and Veterinarian Research I.P. (INIAV)
Slovakia	Central Control and Testing Institute in Agriculture, Bratislava
Slovenia	Ministry of Agriculture in cooperation with University of Ljubljana, Biotechnical Faculty, Centre for Soil and Environmental Science (ULBF), Agricultural Institute of Slovenia (AIS) and University of Maribor, Faculty of Agriculture and Life Sciences (UM-FKBV)
Spain	Ministry of Agriculture & regional governments. Implementation and support to end users are carried out at the local regional level
Sweden	Swedish Board of Agriculture
Switzerland	Agroscope—the Swiss centre of excellence for agricultural research, affiliated to the Federal Office for Agriculture (FOAG) within the Federal Department of Economic Affairs, Education and Research (EAER)

TABLE 1 (Continued)

Country	Main organisations responsible for formulating fertilisation guidelines
Turkey	Ministry of Agriculture and Forestry
United Kingdom	Agriculture and Horticulture Development Board (AHDB), Department for Environment, Food and Rural Affairs (DEFRA), Scottish Government, Welsh Government, Department for Agriculture, Environment and Rural Affairs Northern Ireland (DAERA). Farm advisory groups, national farmers union representatives and environmental bodies.

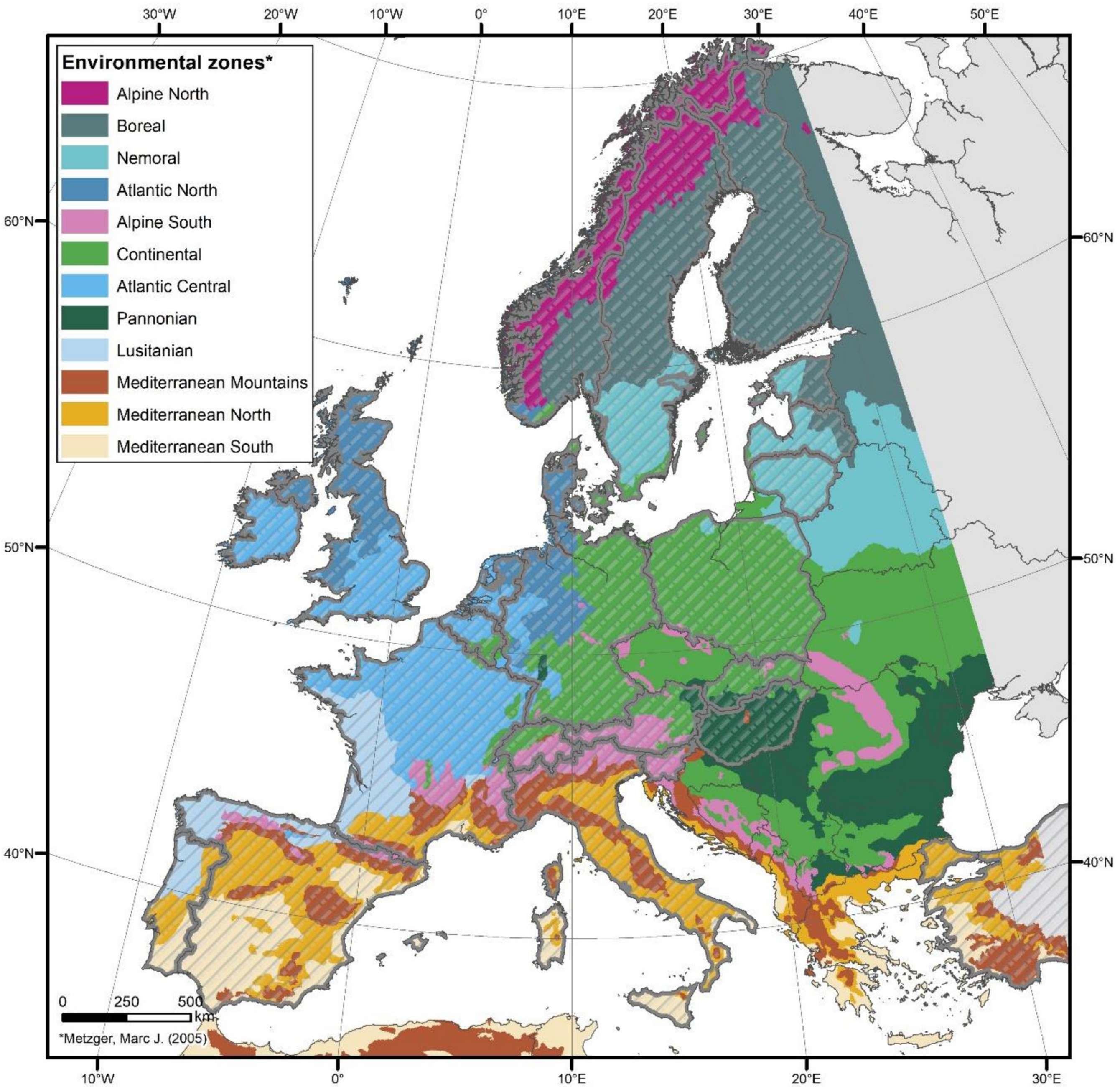

FIGURE 2 Environmental zones (ENZ) of Europe according to Metzger et al. (2005), with countries participating in the questionnaire indicated by dashed lines. In this synthesis, the following ENZ are represented: Alpine North (ALN); Boreal (BOR); Nemoral (NEM); Atlantic North (ATN); Alpine South (ALS); Continental (CON); Atlantic Central (ATC); Pannonian (PAN); Lusitanian (LUS); Anatolian (ANA); Mediterranean Mountains (MDM); Mediterranean North (MDN); Mediterranean South (MDS).

TABLE 2 Main crops grown in each participating country, expressed as %UAA (utilised agricultural area; in alphabetical order).

Country	Main crops
Austria	Permanent grassland (35% UAA), cereals (wheat, rye, oats, barley, triticale: 21% UAA), forage crops (9.3% UAA), corn maize (8.2% UAA), oilseed crops (soybean, oilseed rape, sunflower, pumpkin: 6.4% UAA) and potatoes and sugar beet (2% UAA; Source: Grüner Bericht, 2022).
Belgium	Forage crops (57% UAA; mainly grass from temporary grassland and silage maize), arable crops (mainly cereals, maize, potatoes, sugar beet; 34% UAA) and horticulture (mainly vegetables, fruit and floriculture; 9% UAA; Source: FOD Economy Belgium—Statbel).
Denmark	Spring barley (21.5% UAA), winter wheat (17.5% UAA), grass and grass–clover ley (8.5% UAA), silage maize (6.7% UAA), winter oilseed rape (6.1% UAA), winter rye (3.5% UAA), grass for seed production (3.4% UAA), winter barley (3.1% UAA), spring oat (2.5% UAA), potatoes (2.1% UAA), sugar beet (1.2% UAA), spring wheat (0.7% UAA) and other (23.2% UAA; Source: dst.dk).
Estonia	Wheat (24% arable land), barley (19% UAA), short-term grassland (22% UAA), legume grains (14% UAA) and oilseed rape (11% UAA).
Finland	Grassland (40.5% UAA), feed barley (19% UAA), oats (17.1% UAA), spring wheat (9.9% UAA), malt barley (3.4% UAA), mixed cereals (2.2% UAA), peas (1.8% UAA), winter wheat (1.8% UAA), rapeseed (2.2% UAA), autumn rye (1% UAA), caraway (0.8% UAA), broad bean (0.6% UAA) and reed canary grass (0.2% UAA; Source: Statistics database Luke 2022, (statdb.luke.fi)).
France	Temporary and permanent grassland (47% UAA), wheat (20% UAA), barley (6.5% UAA), annual forage crops (especially forage maize; 6.4% UAA), maize (grain; 5.8% UAA), rapeseed (3.7% UAA), grapes (3.7% UAA) and sunflower seeds (2.6% UAA).
Germany	Permanent grassland (28.5% UAA), wheat (18.0% UAA), maize (15.0% UAA), barley (9.5% UAA), oilseed rape (6.6% UAA), rye (3.5% UAA) and sugar beet (2.4% UAA; Source: Destatis, 2022).
Hungary	Arable crops (82% UAA; winter wheat, spring barley, maize, sunflower and oilseed rape), permanent grassland (15% UAA), orchards (1.7% UAA) and vine (1.2% UAA; Source: ksh.hu).
Ireland	Grassland (82% UAA; permanent grassland, improved grassland (PRG monocultures & PRG + white clover)), rough grazing (10% UAA), cereals (5.9%; spring barley, winter wheat, forage crops, oilseed rape and potatoes), other crops, fruit and horticulture (2% UAA; Source: assets.gov.ie).
Italy	Arable crops (wheat, rice, maize, barley, oat, sugar beet, tobacco, tomato and potatoes; 54.5% UAA); olive (8.7% UAA); vine (5.2% UAA); orchards (apple, pear and citrus; 4.6% UAA); permanent grasslands and pastures (26.7% UAA)
Latvia	Wheat, oilseed rape, rye, oats, barley and legumes
Lithuania	Winter wheat (28.8% UAA), permanent grassland (19.5% UAA) winter rape (11.6% UAA), short-term grassland (5.8% UAA), spring wheat (3.6% UAA), spring oats (2.8% UAA), peas (2.5% UAA), buckwheat (2.0% UAA), beans (1.9% UAA) and maize (1.8% UAA)
Netherlands	Grassland (54% UAA), maize (10% UAA), potatoes (9% UAA), cereals (10% UAA), sugar beets (4% UAA), other arable crops (6% UAA) and horticultural crops (6% UAA; Source: agrimatie.nl)
Norway	Meadow and pasture (67% UAA), grain crops (29% UAA) and potatoes and vegetables (4% UAA)
Poland	Sown area (73.3% UAA), fallow land (1.3% UAA), permanent crops (2.5% UAA), permanent grassland (18.6% UAA), permanent pasture (2.8% UAA) and others (1.3% UAA; Source: Statistical Yearbook of Agriculture, 2002).
Portugal	Arable crops (mainly maize, rice, potatoes and tomato for industry; 26% UAA); permanent crops (mainly olive, citrus, apple, pear and vine; 22% UAA); permanent grassland; 52% UAA; Source: Statistics Portugal (2023)).
Slovakia	Cereals (wheat, barley, rye and oats; 31% UAA), winter rape (6% UAA), sunflower (3% UAA), maize (corn and silage; 10% UAA), perennial fodder (5% UAA) and permanent grasslands (21% UAA).
Slovenia	Permanent grasslands (57% UAA), arable land (37% UAA) and permanent crops (6% UAA). Maize (corn and silage; 14% UUA), wheat (5% UUA), grass/clover (5% UUA), barley (4% UUA), triticale (1% UUA), oil pumpkin, rapeseed, buckwheat, potatoes, hops and field vegetables (total 7% UUA)
Spain	Cereals (36% UAA), olive tree (15% UAA), forage crops (7% UAA), fruit trees (6% UAA), industrial crops (6% UAA), vineyard (6% UAA), sunflower (4.3% UAA), ornamental crops (4% UAA), grain legumes (3% UAA), vegetables (2% UAA), citrus trees (2% UAA) and rapeseed (0.6% UAA).
Sweden	Cereals (39% UAA), lay and green forage (44% UAA), potatoes (1% UAA), rape seeds (4% UAA) and fallow (6% UAA)

TABLE 2 (Continued)

Country	Main crops
Switzerland	Permanent grassland (58% UAA), small-grain cereals (12% UAA), temporary grassland (11% UAA), silage and grain maize (6% UAA), wine and orchard crops (1% UAA), root crops (potatoes and sugar beet; 3% UAA), oilseed crops (rapeseed, sunflower and soybean; 3% UAA), vegetables and pulses (2% UAA; values from 2021, source: https://2022.agrarbericht.ch/de/produktion/pflanzliche-produktion/flaechennutzung)
Turkey	Field crops (wheat, barley, oat, maize, rice, sunflower, cotton, lentil, dried beans, chickpea, potatoes, onions, soybean, tea, tobacco, sugar beet and sunflower), fruits and vegetables
United Kingdom	Permanent grassland (40% UAA), arable crops (43% UAA), cereals (29.7% UAA), oilseeds (5.6% UAA), potatoes (1.2% UAA), other crops (6.3% UAA), horticultural crops (1.5% UAA; Source: GOV.UK) and bulbs, fruits such as apples, pears, plums and berries. Total croppable area accounts for 54% of UAA. Permanent grassland accounts for 41%.

Plant available K, Mg and Ca

Ammonium acetate (used within 13 countries) and ammonium lactate (used within 10 countries) were the two most commonly used extracts for plant available K, Mg and Ca. The exact detail of methods used within individual countries was not reported, although it was clear that there are variations in methods at individual country level. As with P, it was beyond the scope of this stocktake to make detailed comparisons of calculation methods for individual nutrients.

Carbon

Dry combustion was the most frequently recorded method (75% of countries) of measuring total soil carbon, followed by wet oxidation method (35% of countries; Table 4).

Nitrogen

Soil nitrogen content (total or mineral N) is not routinely measured as a component of formulating fertilisation guidelines in many countries (e.g., Norway, Estonia, the United Kingdom, Ireland). Where required, total N is most commonly measured via dry combustion or by Kjeldahl analysis (wet acid digestion) and mineral N by KCl extraction (Table 6). Instead, other methods and criteria are used to determine plant available N in soil, along with estimating plant demand, and these vary between countries. For example, in the United Kingdom, crop N recommendations are based on a combination of factors such as classification of soil N supply (based on soil type, previous crop, management or rainfall for example), combined with target yields and source of N (organic manures or mineral fertiliser). In Sweden and Norway, a strategy is increasingly used among farmers to determine N deficiency in grain crops during the cropping season using optical sensors. In Sweden, the Yara N Sensor and satellite-based systems such as CropSAT.se/CropSAT.com and Yara AtFarm are also widely used to estimate crop N requirement and its in-field variation during the cropping season for variable rate N fertilisation.

3.3 | Objective 3: Synergies, similarities and differences between systems

In general, common across all countries is the completion of soil analysis, the identification of the nutritional needs of crops, the interpretation of soil test results and formulation of a fertilisation plan in relation to the pedoclimatic conditions. The methods of communication of fertilisation guidelines to farmers vary greatly between countries, some countries providing great detail on how to build the fertilisation plan (e.g., France, Switzerland and Austria). According to answers provided in the questionnaire, other countries, such as Slovenia, use a similar conceptual approach, but the communication is simplified. Most European countries allocate soil analysis results to four to six classes, ranging from low to high nutrient content, but the detail and interpretation of results and how it is presented to farmers vary greatly.

Computer-based nutrient management planning systems to calculate fertiliser timing and rates are becoming more common, both to calculate fertiliser requirements and to disseminate the advice to farmers. Many regions (such as Scandinavian countries) are moving away from tabular outputs for farmers to a more web-based approach for delivering advice. Similarities in current fertilisation guidelines do exist to some extent within specific regions of Europe already, and there is awareness of this among the neighbouring countries. It is the case, for example, in north-west Europe, countries such as the United Kingdom, Ireland, France, Netherlands and Belgium. Italy reported similarities in their fertilisation guidance documents with France, Switzerland and Austria. Changes in fertilisation in northwest Europe are primarily being driven by environmental concerns. Likewise, Spain and Portugal reported known similarities between their systems. However, seven countries reported that common principles may exist between countries, but they were unfamiliar with the details (Figure 3).

TABLE 3 List of plant available soil phosphorus chemical extractant methods recorded by participating countries.

Soil P chemical extraction method	Austria	Belgium (Flanders)	Belgium (Wallonia)	Denmark	Estonia	Finland	France	Germany	Hungary	Ireland	Italy
0.5 M Sodium bicarbonate pH 8.5 Olsen Olsen et al. (1954))				X			X				X
0.1 M Ammonium Lactate 0.4 N acetic acid, pH 3.75 Egner-Riehm Egner et al. (1960)		X							X		
0.02 M Calcium lactate buffered to pH 3.6 with 0.02 M hydrochloric acid at 1:50 ratio DL or Egner-Riehm (1943)								X			
0.43 M nitric acid ISO 17586:2016											
Remoisture of soil 1–2 mL soil + 2 mL water Sissingh (1971)											
0.05 M Calcium acetate + calcium lactate + 0.05 M + 0.3 M acetic acid pH 4.1 Schüller (1969)	X							X			
0.015 M Ammonium fluoride + 0.2 M acetic acid + 0.25 M ammonium nitrate + 0.013 M nitric acid, pH 2.5 Mehlich (1984)					X						X
Sodium acetate acetic acid, pH 4.8 Morgan (1941)										X	
0.03 M Ammonium fluoride + 0.025 M hydrochloric acid Bray and Krutz (1945)											X
1:5 citric acid 2% Dyer (1894)							X				
0.2 M Ammonium oxalate Joret and Hebert (1955)							X				
1:2.5, CO_2-saturated water Dirks and Scheffer (1930)											
0.5 M Ammonium acetate + EDTA 0.02 M pH 4.65 Van den Hende and Cottenie (1960)											
0.5 M Ammonium acetate + EDTA 0.02 M pH 4.65 with 1:5 soil: solution ratio Lakanen and Erviö (1971)			X								

TABLE 3 (Continued)

Soil P chemical extraction method	Austria	Belgium (Flanders)	Belgium (Wallonia)	Denmark	Estonia	Finland	France	Germany	Hungary	Ireland	Italy
0.5 M Ammonium acetate, 0.5 M acetic acid, pH 4.65 Vuorinen and Mäkitie (1955)						X					
0.01 M $CaCl_2$ Houda et al. (1990)											

Soil P chemical extraction method	Latvia	Lithuania	Netherlands	Norway	Poland	Portugal	Slovakia	Slovenia	Spain	Sweden	Switzerland	Turkey	United Kingdom
0.5 M Sodium bicarbonate pH 8.5 Olsen Olsen et al. (1954))						X			X		X	X	X
0.1 M Ammonium Lactate 0.4 N acetic acid, pH 3.75 Egner-Riehm Egner et al. (1960)		X	X	X	X	X		X		X			
0.02 M Calcium lactate buffered to pH 3.6 with 0.02 M hydrochloric acid at 1:50 ratio DL or Egner-Riehm (1943)	X*				X								
0.43 M nitric acid ISO 17586:2016	X*												
Remoisture of soil 1–2 mL soil + 2 mL water Sissingh (1971)			X								X		
0.05 M Calcium acetate + calcium lactate + 0.05 M + 0.3 M acetic acid pH 4.1 Schüller (1969)											X		

(Continues)

TABLE 3 (Continued)

Soil P chemical extraction method	Latvia	Lithuania	Netherlands	Norway	Poland	Portugal	Slovakia	Slovenia	Spain	Sweden	Switzerland	Turkey	United Kingdom
0.015 M Ammonium fluoride + 0.2 M acetic acid + 0.25 M ammonium nitrate + 0.013 M nitric acid, pH 2.5 Mehlich (1984)					X		X						
Sodium acetate acetic acid, pH 4.8 Morgan (1941)													**
0.03 M Ammonium fluoride + 0.025 M hydrochloric acid Bray and Krutz (1945)												X	
1:5 citric acid 2% Dyer (1894)											X		
0.2 M Ammonium oxalate Joret and Hebert (1955)													
1:2.5, CO_2-saturated water Dirks and Scheffer (1930)											X		
0.5 M Ammonium acetate + EDTA 0.02 M pH 4.65 Van den Hende and Cottenie (1960)											X		
0.5 M Ammonium acetate + EDTA 0.02 M pH 4.65 with 1:5 soil: solution ratio Lakanen and Erviö (1971)													

TABLE 3 (Continued)

Soil P chemical extraction method	Latvia	Lithuania	Netherlands	Norway	Poland	Portugal	Slovakia	Slovenia	Spain	Sweden	Switzerland	Turkey	United Kingdom
0.5 M Ammonium acetate, 0.5 M acetic acid, pH 4.65 Vuorinen and Mäkitie (1955)													
0.01 M $CaCl_2$ Houda et al. (1990)			X										

*Until 2022 in Latvia, DL or Egner-Riehm method (extraction with 0.02 M calcium lactate solution buffered to pH 3.6 with hydrochloric acid at 1:50 ratio) was used. *From 2022 ISO 17586:2016 (extraction with 0.43 M nitric acid) is used. To ensure compatibility of the results, a pedo-transfer function is used to recalculate results to DL or Egner-Riehm method. DL or Egner-Riehm should not be mixed up with AL or Egner-Riehm Domingo method (extraction with ammonium lactate solution buffered to pH 3.7 with ammonium acetate at 1:20 ratio).*

**A modified Morgan's method is used in parts of Scotland (0.5 M ammonium acetate/acetic acid adjusted to pH 4.5; MISR/SAC, 1985).

Differences in farm type and management intensity vary between neighbouring countries. As an example (as reported in the questionnaire responses), there are differences in prevalence of forest in Sweden compared to intensively managed agricultural land in Denmark. Compared to Sweden, the farm animal density and availability of manure are much higher in Denmark, and this understandably translates into differences in nutrient management. Spain and Portugal reported being similar in their fertilisation guidelines, while differences with France are more apparent, mainly driven by differences in the type of agro-ecosystems between the countries. For farmers living in border regions between countries, it was recognised by 100% of the countries that it is likely that there are differences in fertilisation regimes operating within close proximity. However, seven countries stated that while they expect that differences exist along border regions, they have not been quantified and the implications have not been reported and discussed among neighbouring countries. Belgium (Flanders) noted that there may be farmers who own land parcels across border areas, and they must comply with different fertilisation guidelines for different land parcels. In the questionnaire responses, both Ireland and the United Kingdom stated that there are different soil tests used between Ireland and Northern Ireland (the United Kingdom) but they were aware that guidelines in general are similar between these countries, with shared environmental concerns and agronomic crop requirements. A final example is in Portugal, where the questionnaire responses detailed that near the border in the south of the country, there are intensive olive groves that are managed by Spanish technicians, using the fertilisation guidelines developed in Spain.

When asked if the differences in fertilisation regimes between neighbouring countries could impact on water quality in cross-border catchments or cross-border nutrient loss, 19 countries answered that yes, it is highly likely that there is an impact on cross-border catchments and the environment and they are aware of scenarios. Four countries answered that there is no impact on cross-border catchments, specific to their country. Estonia stated that due to the hydrological situation, it is unlikely that any effects are observed between Estonia and Latvia. Lithuania and Norway were unaware of any specific situations, but questionnaire responses suggested that perhaps there are gaps in the research to support some of these specific examples.

Restrictions to fertilisation in conservation areas and Nitrate Vulnerable Zones are common across all countries surveyed, as are restrictions on the use of sewage sludge and other waste materials. Separate guidelines on

TABLE 4 Principles and methods of measuring total soil carbon across participating countries.

Country	Dry Combustion (ISO 10694)	Wet Oxidation (ISO 14235)	Loss on Ignition
Austria	X*		
Belgium (Flanders)	X		
Belgium (Wallonia)	X		
Denmark	X		
Estonia	X	X	
Finland	X		X
France	X	X	
Germany	X		
Hungary		X	
Ireland	X		X
Italy	X	X	
Latvia	X		
Lithuania			
Netherlands			X
Norway			X
Poland	X	X	X
Portugal	X	X	
Slovakia		X	
Slovenia	X		
Spain	X	X	
Sweden	X		X
Switzerland		X	
Turkey	X		X
United Kingdom	X		X

*Total C by Dry Combustion (ÖNORM L1080).

the use of organic fertiliser sources, such as composts, exist in the majority of countries surveyed.

3.4 | Objective 4: Potential and barriers for harmonisation of methodologies

Overall, there was unanimous (100%) support among countries for some kind of harmonisation, or standardisation, of fertilisation guidelines between neighbouring countries. However, it was emphasised that this should only be where soil type, growing conditions, crop rotations and yields are comparable. Many of the questionnaire responses alluded to the climatic variation across Europe and the huge influence this has on nutrient cycling and nutrient availability, which in turn influences fertilisation recommendations (e.g., between northern and southern European countries; references presented included Gabriel & Quemada, 2017; Quemada & Gabriel, 2016). The potential benefits of harmonisation and barriers for harmonisation presented by the 23 participating countries are summarised in Table 7.

3.4.1 | Should there be a centralised EU approach to fertilisation management?

Overall, the majority of the 23 countries supported some form of centralised approach to fertilisation management, and it was felt that reflections could begin in this direction; however, there was considerable uncertainty in the form this should take. 30% of the countries surveyed said that no there should not be a centralised approach. The main reason being that the soil and pedo-climatic differences between countries are too great for any kind of successful centralised approach to management. European harmonisation would lead to a change in practical references, which would take time to adapt to and must be considered over many years. This depends on the initial situation per country and the new standards they would

TABLE 5 Methods of measuring plant available K, Mg and/or Ca in soil across participating countries.

Country	Ammonium acetate*	Ammonium lactate (Egner-Riehm)	Sodium acetate	Hydrochloric acid and oxalic acid	0.01 M $CaCl_2$	Cobalt hexamine in combination with NIRS	Mehlich-3	Morgan's	Calcium Acetate Lactate (Schüller)	0.02 M calcium lactate + 0.02 M hydrochloric acid
Austria	X								X	
Belgium (Flanders)		X								
Belgium (Wallonia)	X									
Denmark	X									
Estonia							X			
Finland	X									
France	X		X							
Germany					X					X
Hungary		X								
Ireland								X		
Italy	X						X			
Latvia	X	X								
Lithuania		X								
Netherlands				X	X	X				
Norway		X								
Poland		X			X		X			
Portugal	X	X								
Slovakia							X			
Slovenia	X	X								
Spain	X	X								
Sweden		X								
Switzerland	X				X					
Turkey	X									
United Kingdom	X									

*Includes some country-specific variations in method, but all based on ammonium acetate extraction.

TABLE 6 Methods of measuring soil N in participating countries.

Country	Total N by Dry combustion (ISO 13878)	Total N by Kjeldahl (ISO 112261)	Potentially mineralisable N by ÖNORM L 1204	Mineral N (N_{min}) by 1% K_2SO_4 extraction	Mineral N (N_{min}) by 1 M or 2 M KCl extraction	Mineral N (N_{min}) by $CaCl_2$ extraction	Not measured in routine analysis	Other	No information provided
Austria			X					X*	
Belgium (Flanders)					X				
Belgium (Wallonia)	X	X			X				
Denmark	X				X				
Estonia							X		
Finland									X
France	X	X							
Germany						X			
Hungary					X				
Ireland					X		X		
Italy	X	X			X				
Latvia	X	X							
Lithuania		X			X				
Netherlands		X				X			
Norway							X		
Poland	X	X		X					
Portugal		X			X				
Slovakia		X							
Slovenia	X					X			
Spain	X	X							
Sweden							X		
Switzerland									
Turkey		X			X				
United Kingdom	X	X			X		X		

*Total N by Dry Combustion, but using an Austrian ÖNORM, ÖNORM EN 16168.

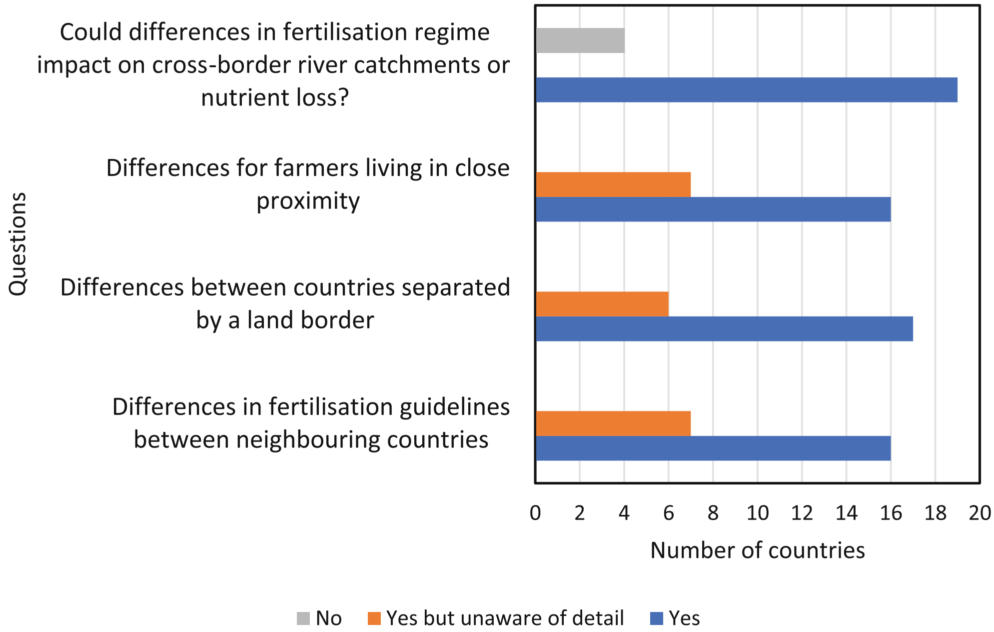

FIGURE 3 Responses by participants to questions on similarities and differences in fertilisation guidelines with neighbouring countries.

have to share. Some countries were supportive of harmonised guidelines but only if there were sufficient opportunities to adjust recommendations to suit local climate and yield potentials. EU-wide knowledge on nitrogen budgeting and its comparability at farm level for the detection of ground and water pollution caused by nitrates was mentioned as an advantage, paired with exchange of scientific knowledge across wider areas of Europe. Several countries commented that to some degree, the current Nitrates Directive has created similarities around N fertilisation across the EU, bound by legal requirements. Certainly, there should be more emphasis on improved sharing of knowledge and the need for decision support tools and nutrient management planning systems available in all countries.

3.4.2 | Precision agriculture

To some degree, precision agriculture is implemented within all countries surveyed. In many regions, the percentage of farmers using precision technology is relatively low, values also varying depending on the specific technology. However, questionnaire responses reported that uptake is increasing, especially for variable rate fertilisation and several decision support systems are now available and in use. In follow-up discussions, questionnaire participants were asked to provide references to published studies to validate their responses where required. France and Germany reported some of the highest adoption rates among countries surveyed and referenced the publication by Paustian and Theuvsen (2017) as an example. In the Netherlands, the experts completing the questionnaire estimated that approximately 15% of the farmers use satellite imagery, soil scans and variable rate fertiliser application, and for Switzerland, 17% of the farmers are estimated to have adopted such technologies. Reference was given to the study by Groher et al. (2020). France has been using satellite imagery for guiding N fertilisation in cereals for a number of years. In Sweden and Denmark, the free of charge platform CropSAT (cropsat.dk and cropsat.se) is being widely used. In Poland, the free of charge platform INTER-NAW is offered to farmers and agricultural advisors for preparation of fertilisation plans and to help balance macro- and micronutrients (N, P, K, Ca, Fe, Mn, Zn, Cu, B and Mo) in soil. What is unique is that it also contains an advisory module for calculating liming needs and phosphorus saturation of soil. Questionnaire responses indicated that an increase in precision agriculture adoption may be expected when the techniques become cheaper, the accuracy improves, the technique becomes easier to use and when legislation becomes more customised and extended to more crops and geographical areas. There is currently much active ongoing research in this area. In Estonia, the questionnaire results reported by their country expert suggested that less than 5%, and likewise in Italy and Hungary, only 1%–2% of the farmers use precision agriculture techniques. However, automated steering on farm vehicles may be used by more than 50% of farmers in Estonia. The value and potential benefit of adopting such techniques is strongly recognised and their application is growing over time. In Scandinavia, Germany, the United Kingdom and Baltic countries, N sensors for nitrogen are used in grain farming. In Sweden,

TABLE 7 Summary table of potential benefits of harmonisation of fertilisation guidelines across Europe and potential barriers to harmonisation, as reported in the questionnaire responses from the 23 participating countries.

Benefits of harmonisation of fertilisation guidelines across Europe	Barriers to harmonisation of fertilisation guidelines across Europe
Improvements in nutrient management and fertilisation recommendations across Europe facilitated by shared knowledge, communication between countries and collective decision-making on best management practices.	Full harmonisation may not be possible and would not be necessary. It is important that harmonisation should not be a goal in itself that prevents progress towards better management.
Harmonisation of fertilisation guidelines could contribute to greater fertilisation planning and budgeting at farm level, particularly in terms of nitrogen. A unified farm-level budgeting of nitrogen across Europe would be desirable.	There are huge difficulties in the ability to align and harmonise guidelines between neighbouring countries. Sharing of knowledge may be a better solution.
Improved management of cross-border catchments and river systems (e.g., the Rhine), through harmonised monitoring, actions and measurement of nutrient inputs within catchments where water quality thresholds are being exceeded.	Fertilisation guidelines and recommendations need to be site and crop specific.
Harmonisation of fertilisation guidelines to manage air quality and transboundary air pollution, for example, ammonia.	The differences between countries in terms of soil types, crops, climate and target yields are so great and this is a huge barrier to harmonisation.
Harmonisation of fertilisation guidelines, based on solid science, would support the development of regional fertilisation guidelines within environmental zones.	Biophysical, social, cultural and economic differences between countries need to be accounted for.
Sharing of knowledge and management practices, for example, the use of novel fertiliser products.	Some questionnaire respondents felt that harmonisation of fertilisation guidelines would not be a priority.
Methods of communication could also benefit from harmonisation. For example, development of digital decision support tools, nutrient calculators, detail of guidance booklets, demonstration farms and webinars.	Sharing of knowledge and well-trained farm advisors was seen as more important than harmonisation by some participants.
Harmonisation of methods for managing soil pH, macro- and micro-nutrients would be beneficial for neighbouring countries with similar soils, crops and climatic regimes.	
Fertiliser guidelines can be harmonised, as long as they are flexible enough to account for situations specific to individual countries.	
Harmonised methods may help facilitate comparisons of long-term data between countries in future.	

questionnaire responses indicated that the 50% of the total acreage of winter wheat is fertilised via variable rate N applications. Many of the countries surveyed consider that precision agriculture using soil and crop sensors and site-specific land management is important in future farming. However, despite many positive views on the potential value of precision technology in future farming, 30% of countries within the questionnaire felt that precision agriculture techniques would not be an appropriate way of harmonising nutrient management and fertilisation practices. These countries emphasised the need to harmonise the basic framework behind the guidelines first, and precision agriculture techniques would then have a place in helping optimise the guidelines thereafter.

3.5 | Objective 6: Evaluation of the importance of knowledge transfer and community engagement

A wide range of knowledge transfer methods for fertilisation guidelines is currently in use. These include articles in farming journals and increasingly via online sources. Targeted mailings, telephone contacts, information meetings and events, on-farm demonstrations and support groups are also in operation. This is an improvement on traditional paper booklet formats, which may have been the only source of information a number of years ago. While online and digital sources greatly increase the potential reach of information, care should always be taken that this is mainly as 'official' sources of information rather than articles that could potentially be misinterpreted or provide conflicting guidelines or reports, based on non-scientific sources. While the effectiveness of different forms of knowledge transfer was not known by those completing the questionnaire, it was generally accepted that different communication approaches vary in their success, depending on the farmer group, or if the fertilisation advice is being used by scientists, policymakers or fertiliser companies for example.

4 | DISCUSSION

4.1 | Stocktake of current fertiliser guidelines across European countries

This study revealed a need for harmonisation of approaches for rational and evidence-based nutrient management and monitoring across Europe. The questionnaire methodology for gathering information on current crop fertilisation guidelines across 23 European countries was hugely beneficial in terms of bringing together experts in soil science and crop nutrition from across Europe to compile this rich and complex dataset. Among other things, this questionnaire provided a unique side-by-side comparison of

1. Key variables influencing how individual countries across Europe formulate fertiliser guidelines for their country, including the influence of climate, soil, cropping system and nutrient loss. This can result in variations in nutrient recommendations, for example, N rate, for the same crop, with comparable soil type and management.
2. The soil test methods used to determine current soil nutrient status and plant requirements.
3. The role of stakeholders, shared learning and the importance of new technologies in making informed nutrient management decisions.

The questionnaire revealed that, currently, there is limited harmonisation or no unified method of formulating fertiliser recommendations, even between neighbouring countries within the same environmental zone. Individual countries operate their own system independently, although common limits on N (and often P also) are shared in terms of meeting Nitrates Directive requirements across many countries. The United Nations (UN) Sustainable Development Goals (SDGs; https://sdgs.un.org/goals) call for greater measuring, monitoring and modelling of nutrient cycling in farmland and the development of tools and interfaces for end users and stakeholders. The findings of the questionnaire demonstrated a lack of EU-wide harmonisation in fertilisation methods, measuring, monitoring and reporting. This is a disadvantage in terms of the ability to compare data between countries and having a standardised method of long-term monitoring of soil nutrient management across Europe. Indeed, although a small number of countries reported a general awareness of the fertilisation practices within their neighbouring countries, the majority of countries in this study reported a lack of awareness in the details of methods outside of their own borders.

The EU has identified the need for a platform of data that will provide the Commission and the broader soil community with knowledge and dataflows that will help safeguard our soils (EU Soil Observatory [EUSO]; https://joint-research-centre.ec.europa.eu/eu-soil-observatory-euso_en). One of the key tasks of the EUSO is to collect high-resolution, harmonised and quality-assured soil information, which can be tracked and through which progress can be assessed. This will support policy decisions in terms of achieving the sustainable management of soils across the EU and the restoration of degraded soils. The questionnaire method and the volume of data collected within the reported study contribute to the objectives of EUSO, by providing a baseline of current status of nutrient management across Europe. It was beyond the scope of this work to compare the full details of fertilisation calculation methods for individual nutrients; however, information on soil test methods for individual nutrients, along with details on the crop, soil and climatic factors taken into account when calculating fertiliser requirements, were compiled.

The questionnaire comprised 46 questions in total, both fact-based questions and subjective questions. The fact-based questions included questions on, for example, soil types, crops and soil test methods. This enabled direct comparisons to be made in the responses to these questions between countries. The subjective questions asked for expert opinions on the advantages and barriers to harmonisation, which were not suitable for advanced statistical interpretation. The questionnaire was completed by experts, selected at individual country level based on their expertise; therefore, their knowledge and opinions were extremely valuable within the context of this study. A small number of published studies have addressed the harmonisation of N and P management specifically (Jordan-Meille et al., 2012; Klages et al., 2020; Nawara et al., 2017; ten Berge & van Dijk, 2009; Tunney et al., 1997). However, no previous published manuscripts have addressed the harmonisation of wider fertilisation approaches, for example, how fertilisation advice is delivered to stakeholders, the use of new technologies and alternative fertilisers.

4.2 | Key variables influencing fertiliser guidelines

It is well known that agro-climatic regions exist across Europe, with a number of countries identified within each environmental zone. The level of detail provided in the questionnaire responses by each country on soil types and cropping system varied considerably. However, follow-up detail was obtained in order to make meaningful comparisons between countries. A factor that was particularly striking was the huge number of soil series present at individual country level. This was almost impossible to summarise succinctly within a results table and also highlighted the difficulty this presents when harmonising or standardising soil data.

4.3 | Soil extraction test methods for P, K, Mg and Ca

There is a lack of published articles comparing analytical methods for measuring plant available K, Mg and Ca across European countries, despite the fact that this study showed that a large number of soil tests exist, with further adaptions to tests at individual country level. Efforts have been made by the Global Soil Laboratory Network (GLOSOLAN), established in 2017, to build and strengthen the capacity of laboratories in soil analysis globally and respond to the need for harmonising soil analytical data. In recent years, a number of publications have compared soil test methods for P (Buczko et al., 2018; Jordan-Meille et al., 2012; Nawara et al., 2017; Steinfurth et al., 2021; Steinfurth et al., 2022; Tóth et al., 2014), and it is widely known that at least 10 soil P tests are used across European countries, as shown in the present study. It has also been known for a number of years that there is often poor correlation among those tests, but alternatives or resolutions have not been forthcoming. Jordan-Meille et al. (2012) presented apparent contradictions in the interpretation of soil-P test values and more than 3-fold differences in the P fertiliser recommendations for similar soil-crop situations. To date, there is no unified legislation at European level defining the maximum P amount applicable to agricultural soils due to the different fate of P applied to acidic or calcareous soils and the differences in the analytical methods as well as the strength of the extractants.

The experts in the current study reported that having standard soil tests across Europe would facilitate the exchange of scientific data, creating real and meaningful comparisons. This had been highlighted by Tunney et al. (1997). However, the questionnaire responses reasoned that the principle of soil testing involves the characterisation of plant available nutrients by chemical extraction. Even at a country or regional level, there are complex discrepancies and variability when quantifying nutrient pools using different extracting solutions: consequently, standardising nutrient extraction methods all over European countries appears difficult since national methods are sometimes highly consolidated and responsive to specific soil pedological characteristics. In terms of soil P as an example, Nawara et al. (2017) stated that most soil tests for available P perform rather poorly in predicting crop response, but no soil test was clearly superior to the others.

More than one soil P test operating at individual country level was reported by a number of countries within this study. Bell et al. (2005a, 2005b) presented evidence of where within-country soil type differences can result in variances in the effectiveness of a particular soil test designated as the country-specific test. Including soil parameters such as texture and soil organic matter, in addition to plant available P content, was suggested by Buczko et al. (2018) as helpful to improve P fertilisation recommendations. Differences in cross-border soil test methods can present challenges for managing shared waterbodies. This becomes problematic where there are contrasting fertiliser recommendations between neighbouring farms in cross-border regions and where there are water quality issues relating to agricultural nutrient loss (Vero et al., 2021).

4.4 | Soil test methods for C and N

While not an essential component of fertiliser recommendations, this stocktake study also revealed differences in methodologies for measuring and interpreting soil carbon. This will be very important going forward as we work towards Net Zero targets, improving soil health and nutrient management and the importance of soil as a sink for carbon (Poeplau et al., 2022; Smith et al., 2020). In terms of national carbon accounting, it would be very important that carbon accounting methods are standardised and follow the same protocols (FAO, 2020). Until recently, for national inventories, carbon budgets are (almost always) modelled, not measured. The introduction of a defined set of soil health indicators per country would require thresholds, measuring, monitoring and reporting to be harmonised, including for nutrient use and nutrient limits (Lehmann et al., 2020).

4.5 | Potential for harmonisation of methodologies and barriers to harmonisation

It became clear during the stocktake that there are many different aspects to questions on why harmonisation of current fertilisation guidelines should be considered. Experts completing the questionnaire raised concerns around obvious differences such as soil type, crop and climatic factors, which determine fertilisation strategies, and would be difficult to change, and there are good reasons not to change them. However, the growing importance of the environment and climate change and the need to create a roadmap towards climate-smart sustainable management of agricultural soils give us greater incentive and reason to question current practice.

Tighter legislation on fertiliser use, particularly manure application in intensive animal production areas, is viewed as being crucial to achieve further reductions in surplus nutrient input and emissions across Europe (ten Berge & van Dijk, 2009). A better foundation to fertiliser recommendations is necessary. The large differences in fertiliser recommendations, for example, N fertiliser recommendations for individual crops, were recognised by the experts completing the questionnaires and have been discussed within other publications. For example, ten Berge and van Dijk (2009) summarised the findings of a workshop held in the Netherlands in 2009, where they discussed ways in which nutrient losses from agriculture could be reduced. ten Berge and van Dijk (2009) summarised that, given the important role of N recommendations, an international comparative audit of the science behind recommendations would be highly relevant. Experts completing the current study agreed that there is little common EU-wide knowledge on nitrogen budgeting and its comparability at the farm level for the detection of ground and surface water pollution caused by nitrates and the monitoring of mitigation measures. This had also been reported by Klages et al. (2020). There is some flexibility within the Nitrates Directive for Member States, which is positive, but Klages et al. (2020) recognised that a more integrated approach to nutrient management is required. For example, this could involve stronger exchange of scientific knowledge, with perhaps a more unified system of registration, monitoring and inspection for wider areas in Europe. However, a consensus on agricultural soil management practices would need to be in place first. The development of more harmonised fertilisation guidelines, which at least overcome discrepancies linked to overly empirical evaluations and implement an agreed selection of scientifically based methods, would be extremely important to allow truly balanced mineral and organic fertiliser inputs. The focus here is not confined to N and P.

However, change in current practice (soil tests and fertilisation recommendations) would need to be considered over time. The assimilation of new methods by farmers is a crucial issue when in many cases even the current national methods are variably implemented within their own countries. Some countries within the stocktake felt that for detailed guidelines and regulations, there should *not* be a centralised EU approach because conditions are too different. Best management practices for both production and environment are those adapted to local conditions. Analytical methods, purpose and possible gains must be carefully evaluated, and an EU-wide evaluation of trial results would need to be coordinated. The local adaptation needed at the farm and field scale for efficient use of resources should be considered. Current differences in fertiliser recommendations may result in, for example, an optimal N rate in some countries being substantially higher for the same crop and the same harvest than in other countries (Jordan-Meille et al., 2022). To establish such circumstances and investigate plausible reasons and environmental and economic consequences are of considerable interest. Ideally, there would need to be fertiliser response trials for contrasting crops, environments and soil types.

4.6 | Alternative fertilisers and new technologies

To reach the EC target reduction in nutrient losses by at least 50% and a reduction in chemical fertiliser use by at least 20% by 2030, alternative fertiliser sources will need to be considered. Many studies in recent years have assessed the fertiliser replacement value of a number of new and innovative products such as composts (Agegnehu, Bass, et al., 2016), dairy processing sludges (Ashekuzzaman et al., 2021; Börjesson & Kätterer, 2018; Delin, 2016) and biochars (Agegnehu, Nelson, & Bird, 2016; Arif et al., 2017; Biederman & Harpole, 2013; Gao et al., 2022; Ye et al., 2019). Many of these products are high in nutrients and offer important benefits for soil health. However, the content and plant availability of nutrients between products are highly variable. Questionnaire responses indicated that many new fertiliser products are commonly known as 'soil conditioners' rather than 'fertilisers' but there is currently no clear unified definition or guidance across Europe on many of these alternative fertiliser products, their use, application rate or nutrient value. A benefit of harmonisation of fertilisation guidelines across Europe would be to include shared learning in the use of alternative fertiliser products, for example, on demonstration farms or in a guidance booklet that could be accessed across countries for specific crops.

Precision farming techniques were recognised by experts within this stocktake study as being important in future agricultural management. Precision farming techniques are continuously developing and offer rapid diagnosis of crop N status, for example, reflection measurement by crop sensing and/or soil N status and variable rate fertiliser applications (Argento et al., 2022; Higgins et al., 2019; Spiegel et al., 2020). Further promising technologies include targeted placement of fertilisers near plant roots along with better timing and dosage based on crop/soil indicators. Precision agriculture developments, by increasing efficiency within agricultural systems, will directly impact fertiliser recommendation systems going forward. Instead of blanket country-specific recommendations, future fertiliser recommendations *should* take into consideration farm-specific decision support systems, integrating site, soil, plant and climatic data during the growing season. Cowan et al. (2020) estimated that up to 20% savings could be made by not applying N where it is unnecessary to do so. The new Farm to Fork Strategy and its aim to reduce N fertilisation by 20% will further contribute to more targeted N fertilisation. Recommendations also need to be updated regularly due to improved cultivars and crop varieties that differ in their nutrient uptake and demand. In future, the continued development of artificial intelligence and high-performance computing could have more of a role in the monitoring of soil and crops, with upscaling of field data to catchment and national scale. Proximal sensors provide measurements of ground data, which is particularly useful for generating data on soil properties. The fusion of data from proximal and remote sensing systems, along with real-time samples or long-term benchmark monitoring sites, can be very powerful (Smith et al., 2020). Predicting nutrient levels has been suggested as being feasible with sensor fusion and information from several soil and crop sensors at once. Multi-sensor platforms for sensing soil are likely to play a bigger role in future (Escolà & Kerry, 2021). For farmers to take advantage of these digital opportunities, training courses and access to user-friendly tools and smartphone apps are indispensable.

4.7 | Knowledge transfer, stakeholder engagement and decision support systems

Shared learning, knowledge transfer, stakeholder engagement and development of decision support systems were viewed as one of the potential advantages of harmonisation of fertilisation guidelines by experts engaged in this study. There have already been attempts to develop these systems across Europe. Best4Soil (https://www.best4soil.eu/) is a network of practitioners for sharing knowledge on prevention and reduction of soil-borne diseases. This is an example where a community of practice network could be built across Europe, in this case for fertilisation methods, through which growers, advisers, educators and researchers working within soil science and crop nutrition could be connected. The Best4Soil network promotes knowledge of best practice, through a website and as organised meetings across Europe. Communities of practice (CoP) have been created to deal with regional-specific issues.

The EU FaST tool (https://fastplatform.eu/) is a digital service supported by DG Agriculture and Rural Development, the EU Space Programme and the EU ISA Programme. The vision of the FaST tool is to provide solutions for sustainable and competitive agriculture based on data spatialisation (Copernicus and Galileo) and other public and private databases. Fertilisation recommendations are within the FaST applications, based on overlaying farm data with Copernicus/Sentinel imagery. However, spatial imagery information is not always relevant to inform soil nutrient availability (particularly soil P). The FaST tool is proposed under Good Agricultural and Environmental Conditions (GAEC) as part of the new Common Agricultural Policy (CAP) proposal. A farm-gate balance module could be integrated into FaST as a quick and easy digital tool that could be used by all countries. However, much research and development are still required in integrating these methods on farms. The use of smartphone apps, nutrient management planning computer programmes and precision agriculture principles could possibly be used as the basis for harmonising management practices across EU countries and more specifically within discrete environmental zones.

The technical and economic benefits still need to be quantified. For the best global agricultural and environmental outcomes, we need to question whether the priority is more technology for a small number of advanced farmers or an effective implementation of simple, moderately performing methods by a greater number. While promising, many of the participants within this stocktake stated that precision agriculture may not be able to replace the importance of accurately measuring plant available nutrients by traditional extraction methods.

5 | CONCLUSIONS

The overall objective of this study was to assess the potential for harmonising methods used for formulating fertilisation guidelines between neighbouring countries and across regions in Europe. Accountability of nutrient use at field, farm and national level is increasing in importance. There would be many benefits of a more harmonised approach to fertilisation recommendations across Europe, such as improved management of cross-border catchments and river systems and an agreed selection of scientifically based methods and standards. However, it is unclear as to what exact form the harmonisation would be in. Full standardisation is unlikely to be possible or desirable. Several countries in this study felt that it would be inappropriate or unnecessary to attempt to harmonise fertilisation guidelines due to the significant differences in soil and climatic variables across Europe. However, by sharing principles of soil monitoring, analytical methods and technological advances, there may be beneficial outcomes for both production and the environment. Harmonised approaches would increase comparability of data between countries and enable a more unified European approach for seeking climate-smart sustainable management of agricultural soils.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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