EIP-AGRI Focus Group

Digital tools for sustainable nutrient management

STARTING PAPER

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1. Introduction

The **Farm to Fork strategy** under the **European Green Deal** identifies the excess of nutrients in the environment as a major source of air, soil and water pollution, negatively impacting biodiversity and climate. The European Commission aims at reducing nutrient losses by at least 50%, while ensuring there is no deterioration in soil fertility. This will reduce the use of fertilizers by at least 20% by 2030. The gross nitrogen balance is an important indicator for the quantified Green Deal target.
Improved nutrient management as part of more sustainable farming systems is included in the green architecture of the future Common Agriculture Policy (CAP), contributing to several specific objectives of the policy (web1). In particular, the new CAP Regulation introduces the Farm Sustainability Tool for Nutrient Management referring to digital application(s) that provide on-farm decision support on plant nutrition management, with focus on nitrogen and phosphate. The tool(s) will provide information on nutrient balance and soil at field scale, as well as relevant Integrated Administration and Control System data and legal requirements on nutrients. In addition, these developments provide an opportunity to speed up farmers' uptake of digital solutions going beyond the sphere of nutrient management, adding and connecting to other potential functionalities.

In this context, the EIP-AGRI Focus Group (FG) on 'Digital tools for sustainable nutrient management' aims to identify good practices and inspiring initiatives developing, promoting and facilitating the use of digital applications for an enhanced farm nutrient management. The FG will concentrate on the following tasks:

- Map the digital farm tools already in place, or under development
- Asses the uptake level and usability of these tools among farmers
- Identify the data needs and existing data gaps for an efficient and cost effective use of these tools
- Address the main obstacles for tools uptake by farmers
- Highlight inspiring examples for tools integrating different datasets (both public and private domains)
- Explore which other technical and environmental aspects could be addressed by these tools (regardless of the current field of implementation)
- Propose potential innovative actions and ideas for Operational Groups to stimulate the development, improvement, uptake and use of these tools at farm level
- Identify needs from practice and possible gaps in knowledge

The outcome of the Focus Group will be a report published on the EIP-AGRI website.

This starting paper serves as a background document to prepare the first meeting of the FG, which will take place on 15 and 16 March 2022. The document aims to:

- establish a common understanding on the purpose and scope of the Focus Group
- identify some preliminary issues and key questions for discussion at the first Focus Group meeting
- present an overview of the available knowledge on the digital tools for sustainable nutrient management, which will serve as a preliminary basis for the Focus Group final report.

The next section provides some insights in the policy context and a summary on the nutrient management status in the EU. Chapter 2 provides an overview on the level of use of nutrient management plans. Chapter 3 presents the various relevant technologies available for supporting nutrient management and discusses their strengths, challenges and opportunities. Finally, in Chapter 4, the paper very briefly explores the environmental domains to which those tools may contribute.

1.1 Policy background

The European Green Deal

The European Green Deal (EGD) is a plan to make Europe the first climate-neutral continent, by 2050. The EGD is a package of measures that should enable European citizens and businesses to benefit from sustainable green transition. Measures are ranging from ambitiously cutting emissions to investigating in

cutting-edge research and innovation to preserve Europe's natural environment. Achieving sustainable natural resources management will be key to reach many of the EGD goals.
Different strategies and initiatives implementing the EGD are relevant for this Focus Group. The Biodiversity Strategy; the Forestry Strategy and the proposal for a new Regulation to curb EU-driven deforestation and forest degradation, the Zero pollution action plan and the Chemical's Strategy or the Circular Economy Action Plan are the most relevant.
Among them, the new EU Soil Strategy for 2030 is a key deliverable of the EU Biodiversity Strategy, since healthy soils are the foundation for 95% of food, they host more than 25% of biodiversity and are the largest carbon pool on Earth. The EU Soil Strategy defines concrete measures for protecting, restoring and sustainably using soils. To achieve these, it proposes voluntary and legally binding measures. Among the goals are to increase soil carbon in agricultural land, combat desertification, restore degraded land and soil, and ensure that by 2050 all soil ecosystems are in a healthy condition. The strategy calls for the same level of protection to soil as it exists for air, water and marine environment. The Strategy mobilizes the necessary societal engagement, financial resources and shared knowledge, and promotes sustainable soil management practices and monitoring (web5).
The EGD will also support the achievement of the United Nation's 2030 Agenda for Sustainable Development, which has been adopted by all member states in 2015 and provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its core 17 Sustainable Development Goals (SDGs) have been identified, which are an urgent call for action by all countries in a global partnership (web3).

The Farm to Fork Strategy

At the heart of the EGD the Farm to Fork Strategy aims to make food systems fair, healthy and environmentally-friendly, accelerating our transition to a sustainable food system.

Fig. 1. Elements of the Farm to Fork strategy Source: https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en

The Strategy has a strong focus on nutrient management, since the aim is to reduce nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility. This will reduce the use of fertilisers by at least 20% by 2030. This goal will be achieved by implementing and enforcing the relevant environmental and climate legislation, by identifying with Member States the nutrient load reductions needed to achieve these goals, applying balanced fertilisation and sustainable nutrient management and by managing nitrogen and phosphorus better throughout their lifecycle.
The Commission will develop with Member States an integrated nutrient management action plan to address nutrient pollution at the source and increase the sustainability of the livestock sector. The Commission will also work with Member States to extend the application of precision fertilisation techniques and sustainable agricultural practices, notably in hotspot areas of intensive livestock farming and of recycling of organic waste into renewable fertilisers. This will be done by means of measures which Member States will include in their CAP Strategic Plans such as the Farm Sustainability Tool for nutrient management, investments, advisory services and of EU space technologies (Copernicus, Galileo) (web4).

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The Common Agricultural Policy (CAP)

To consolidate the role of European agriculture for the future, the CAP has evolved over the years to meet changing economic circumstances and citizens' requirements and needs. The new CAP was formally adopted on 2 December 2021, and will enter into force on 1 January 2023. The new CAP supports agriculture in making a much stronger contribution to the goals of the European Green Deal, with higher green ambitions by, among other aspects, an enhanced conditionality, stronger incentives for climate-and environment-friendly farming through the eco-schemes and a reinforced contribution of rural development funds to measures to support climate, biodiversity, environment and animal welfare.

In addition, Member States should ensure that there are Farm Advisory Services (FAS) tailored to the various types of production. Farm advisory services shall be integrated within the interrelated services of farm advisors, researchers, farmer organisations and other relevant stakeholders that form the Agricultural Knowledge and Innovation System (AKIS). In order to support both the agronomic and the environmental performance of farms, FAS should advise farmers on nutrient management, focused on nitrogen and phosphate, with the help of a dedicated electronic Farm Sustainability Tool which should provide on-farm decision support.

Horizon Europe

Horizon Europe, the EU framework programme for research and innovation for the period 2021-2027, is one of the tools to help achieve the SDGs and the goals of the EGD. It facilitates collaboration and strengthens the impact of research and innovation (web6). As part of the Horizon Europe programme new instruments are implemented. One of these are the EU missions. A mission is a set of measures to achieve bold, inspirational and measurable goals within a set timeframe. These missions represent a new channel to connect research and innovation, practice tests on the ground, training and monitoring (web7). In September 2021 the EU launched 5 EU missions as part of Horizon Europe. One of these missions is the 'A Soil Deal for Europe', which very well connects to the EU's ambition to lead on global commitments, notably the Sustainable Development Goals (SDGs), and contribute to the European Green Deal targets on sustainable farming, climate resilience , biodiversity and zero-pollution. It is also a flagship initiative of the long-term vision for rural areas. In addition, multiple Horizon candidate partnerships are connected to the topic of the Focus Group. European Partnerships bring the European Commission and private and/or public partners together to address some of Europe's most pressing challenges through concerted research and innovation initiatives. Among the candidate partnerships the one on 'Accelerating farming systems transition: agroecology living labs and research infrastructures' and the 'Agriculture of data' are very well connected to nutrient management goals (web8).

1.2 Nutrient management in the EU

Despite the fact that the number and area of organic farms is continuously increasing in the EU, the fertiliser usage is still slightly increasing in the last decade. Nitrogen application increased by 1.9% between 2008 and 2018, whereas phosphorous usage has declined by 1.2%.

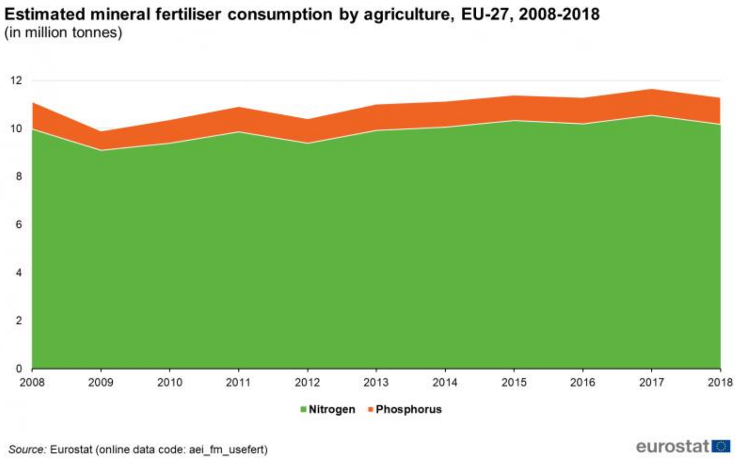

Fig.2. Estimated mineral fertilizer consumption by agriculture EU-27, 2008-2018 (Source:Eurostat)

In EU agriculture, a key challenge for nutrient management is to ensure that the necessary amount of nutrients are available at the right time, and that excess usage of nutrients are reduced and prevented to enter waterbodies. The presence of excess nutrients in ecosystems is harmful to the environment:

- An excess of nitrogen in surface water leads to excessive plant and algal growth, producing eutrophication. Eutrophic water bodies can suffer biodiversity losses and fish deaths.
- Nitrate concentrations in groundwater pose risks to livestock and human health.
- Nitrogen volatilisation contributes to higher concentrations of nitrous oxide (N2O), a potent greenhouse gas, and can lead to soil and water acidification, potentially affecting crop yields and biodiversity (Goulding, 2016).
- A phosphorus surplus is associated with environmental risks as excess P can lead to surface water contamination due to runoff and soil (Bomans et al., 2005). While phosphorus concentrations in water do not pose a direct risk to human health, they are an indirect risk as they favour the growth of cyanobacteria and algal blooms in bodies of water. An excess of algae in water bodies diminishes the amount of oxygen available for other organisms and leads to biodiversity losses and fish deaths. Cyanobacteria can produce toxic substances that can affect human and animal health (Chorus, 1999; Hitzfeld, 2000, web9).

In addition, EU agriculture is responsible for 94% of ammonia emissions (2015) (largely from the storage and application of manure and fertilisers), and 70% of nitrogen entering EU rivers and lakes. Climate impacts are also notable, with over 2% of the total EU greenhouse gas (GHG) emissions arising from artificial fertilisers. This is around 20% of all GHG emissions from agriculture. Besides the environmental and climate effects, the excessive land use and fertiliser usage has also effect on soil health indicators, and yield potential among others. Intensive agriculture reduces soil biodiversity through several mechanisms (e.g. physical disturbance, compaction, lethal and sub-lethal impacts of pesticides and herbicides on the soil biota, and inorganic fertilisers), making soils less efficient, more sensitive to weather events such as extreme drought and rainfall, and reducing organic matter (Tsiafouli et al., 2015).

A cross-EU study, with an experiment involving 114 arable wheat fields across Europe, showed that adding mineral fertiliser and pesticides had strong effects on yield, but that in fields with higher levels of soil organic matter (SOM) the fertilisers had less effect (Gagic et al., 2017). Thus improving soil quality and soil health should be a priority over increased fertiliser usage.

In that regard, the EU has been controlling the fertiliser usage on arable land, and has been intensively using for example nutrient management plans (NMPs) as a monitor and control tool. NMPs have been in use in the CAP for several years. For example, they have been supported in basic agri-environment schemes in the two previous programming periods, as well as forming part of the Statutory Management Requirements (SMR) of Cross Compliance (Regulation (EU) No 1306/2013) – notably SMR1 in relation to the Nitrates Directive (Council Directive 91/676/EEC) (web10).

Fertiliser prices can highly affect their usage. Recent natural gas price increases in the EU and worldwide has been causing fertiliser-plant cutbacks and resulting in record-high nutrient prices, and also a deficit of about 9% of EUs annual nitrogen-fertiliser needs. The increase will most probably affect food prices (Fedorovina et al. 2022) especially if the yields are affected either by nutrient deficiency or negative climatic events.

Fig.3. European fertilizer prices 2019-2021 (Source: Fedorovina et al. 2022)

2. Nutrient management plans in the EU

Nutrient management plans (NMPs) set out the required soil nutrient management needs in a given area and how those needs can and should be met through specific actions. In the case of nutrient management in agriculture, the plans address the need (and in some cases requirements under EU law) at the farm level to ensure that the nutrients applied to land in a given area do not leach out (diffuse) into soils or surface and ground waters. They thus include appropriate application rates, times, locations and practices. Nutrient management plans are primarily aimed at the farm or holding level but can be applied to broader areas where collective action may be needed, or where nutrient management is critical to achieving objectives in a particular area, such as a water catchment or Nitrate Vulnerable Zones (NVZ). The main benefits of nutrient management plans are:

- The assessment of the nutrient requirements of different crops is undertaken prior to the application of fertilisers. This helps to raise awareness about resource efficiency and the use of finite resources, such as phosphorous;
- Nutrient requirements and needs are seen in the context of the capacity of the crops to utilise those nutrients and the land to absorb any excess, such as in relation to soil type, slope or proximity to water courses. This helps to improve knowledge for farmers and land managers about the implications of inappropriate use of nutrients in relation to soil and water objectives, as opposed to just crop requirements;
- Farmers and advisors are able to identify actions to more effectively manage nutrients and thus support implementation and targeting of activity on farms; and
- Inspectors and the competent national authority are allowed to check and review the approaches being taken on a farm or broader areas, such as a water catchment or NVZ.

Management plans that address nutrients or aspects of nutrient management have taken a variety of forms, including soil management plans, water management plans, crop protection management plans and manure management plans (web10).

NMPs are sometimes part of other, broader management plans, such as River Basin Management Plans (RBMPs) required by the Water Framework Directive, where Member States are required to develop plans to demonstrate how they will reach good status of their water courses and set out many of the actions required at the local level.

In the previous EU programming period (2014-2020), in some Member States across the EU NMPs (and other types of management plans) were developed as a response to the implementation of existing Regulations and Directives such as the Nitrate Action Programmes required by the Nitrates Directive. In these cases, NMPs become a requirement of cross compliance (through the Statutory Management Requirements). In addition some Member States have also chosen to use Rural Development Programmes (RDP) to develop and implement management plans and associated actions, often through the agri-environment-climate measure. In addition, the geographical area over which NMPs are required in a given Member State under national law can vary (even through the transposition of the same EU Directive). For example, most Member States require NMPs to be implemented as a result of the Nitrates Action Programme and only within NVZs. In some cases, implementation of NMPs extends to the whole country or region.

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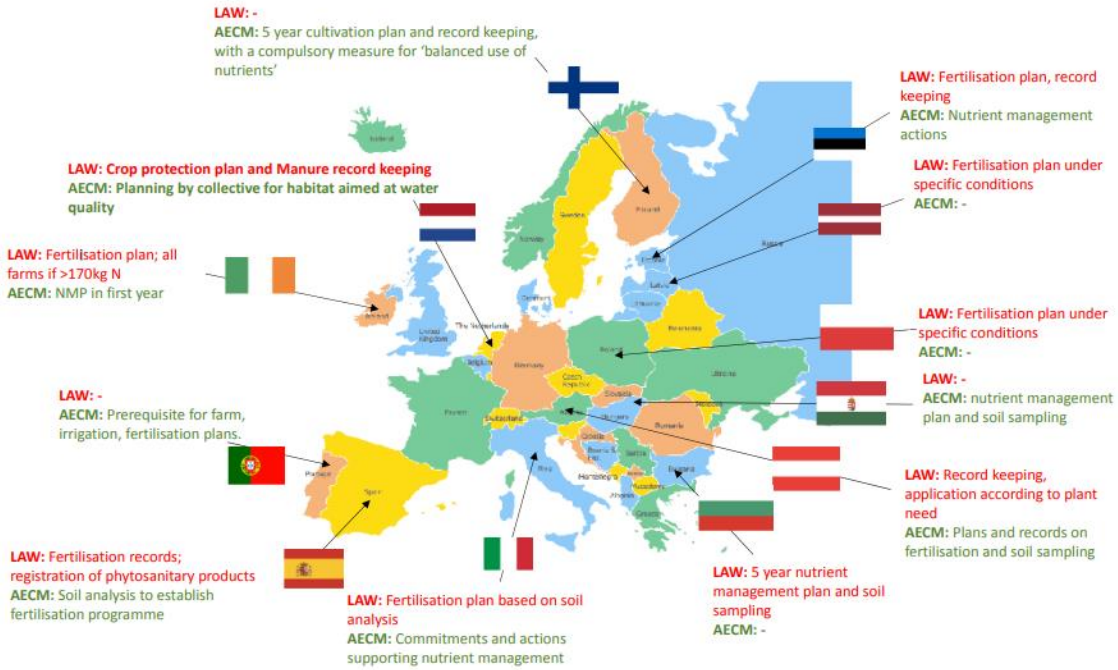

Fig. 4. Location of nutrient management plans in national law or under AECM (Source: web10)

In Finland, national funding was used to support the design of RDP measures for nutrient management by assessing the potential of using nutrient field balances in nutrient management plans. Under the agri-environment-climate measure (AECM), RDP support has been made available in some Member States (e.g. Hungary) to provide the evidence base needed to support the development of NMPs. This adaptable measure has also been used to provide a range of related activities addressing nutrient management that can help implement NMP actions, whether set out in national law or in RDPs.

RDP support has been also used to build the technical capacity of both farmers and advisors to support the development of nutrient management planning, as well as providing support for the implementation of new technologies and machinery, such as direct slurry injection.

Beyond RDP support, LIFE funding has been used effectively in Spain to demonstrate the benefits of nutrient management (through organic farming and crop rotations) and how these can be sustainable without the need for CAP support, as well as demonstrating the potential for making accessible all the available technical knowledge for self-management through a web tool (web10).

As part of the new CAP and as mentioned before, farm advisory services shall provide support, at the latest as from 2024 for the use of a Farm Sustainability Tool for Nutrients, described as any digital application that provides at least:

- (i) a balance of the main nutrients at field scale,
- (ii) the legal requirements on nutrients,
- (iii) soil data, based on available information and analyses, and
- (iv) data from the integrated administration and control system (IACS) relevant for nutrient management.

In addition, support for rural development will continue to fund land management payments, investments, knowledge-building, innovation and cooperation relevant to nutrient management (web11).

3. Tools and techniques to support nutrient management

During the last decades, many technological advancements have been helping farmers and advisors for better nutrient management planning (timewise, location- and material-wise). The adoption of these techniques varies a lot across regions and countries. With the EGD goals and the increasing fertiliser prices, the adoption rate and speed of these tools and techniques will most likely increase. In this context, it is important that these tools are reviewed and validated and that a roadmap is drawn for farmers to not only achieve the environmental related goals but also to keep or increase their profitability.

3.1 Management software and online tools

Lately with the adoption of digital tools many farm management nutrient planning and other decision support tools have been available to farmers and consultants. They are provided by government bodies, private companies, and nonprofit organizations. These tools are aimed to support farmers in nutrient management, along with varying aspects of management, such as crop protection, irrigation etc. With the use of cloud service based data collection and big data techniques, these decision support tools (DSTs) are more and more evolved and can provide very accurate recommendations and predictions. These applications have different input demands to support farming, such as soil samples, yield maps, satellite images, different sensory data, etc., along with the information on the produced crop, and used input materials.

The number of such tools is increasing daily, and many are only available in national languages. In 2016 Rose et al. already identified 395 DST tools available for farmers and advisors in the UK. The H2020 Fairshare project provides an inventory of existing Digital Advisory Tools and Services (DATS). DATS are technologies which include computer and mobile phone applications and services. They may stand alone, on individual devices, or be connected via the web. Their primary function is to assist advisors to deliver a farmer-focused, decision support services or to assist in administrative or communication tasks. Currently 197 DATS are available on the platform, with many of those focusing on nutrient management (web12).The European Network Smart-AKIS aims to mainstream Smart Farming Technologies among the European farmer community and bridge the gap between practitioners and researchers on the identification and delivery of new Smart Farming solutions to fit the farmers' needs. Currently 200 Smart Farming solutions are showcased and assessed on its Smart Farming Platform, many of them related to nutrient management (web13).

Decision support systems have been proven useful in different domains of agriculture, such as pest management, nutrient management planning, farm economy, livestock, and crop management (Jones et al., 2017a,b). As an example, in the UK 49% of farmers use some kind of decision support tool to inform decisions (Rose et al, 2016) although many of these tools are as simple as weather forecasts.

Debeljak et al (2019) lists a variety of examples, such as MarkOnline in Denmark (Bligaard, 2014), Mesp@rcelles in France (APCA, 2019), NMP Online in Ireland (Teagasc, 2016), AgrarCommander in Austria (AGES, 2019), and Web Module Düngung in Germany (LWK Niedersachsen, 2019).

Many of these DSTs can be characterized as "single solution" DSTs that provide limited data to improve only a specific aspect of farm management practices and lack an integration of sustainability aspects (Eichler Inwood and Dale, 2019).

Not only the single solution method is an issue with DSTs. Another limiting issue, as stated by Jones et al (2017a, b), is the scarcity of data. Data are the foundation for all agricultural systems analyses. The lack of sufficient data and restricts the capabilities of existing models to include factors of importance. They also indicate that data limitations are more important than gaps in conceptual theories and approaches. Although Debeljak et al (2019) argue that limitations of current agricultural system models and tools are more strongly rooted in inadequate data than in knowledge gaps. This limitation restricts users' confidence in the models' abilities to provide reliable results and thus their use for decisions or policies.

Examples of decision support tools with nutrient management options

Some widely used tools, globally available, are listed below. The tools' descriptions are based on information offered by the providers:

BAYER Climate FieldView
Climate FieldView can integrate data from satellites, field sensors, irrigation systems, drones, and other input sources and provides farmers with detailed, real-time assessments of growing conditions and crop health to support a sustainable, abundant harvest. Although mainly focusing on row crops, and especially on seeding rates, the application has a nutrient management toolbox to assist farmers plan their applications, using mainly satellite imagery. As of March 2021 the platform is adopted by farmers in more than 20 countries and on more than 60 million subscribed hectares globally (150 million acres).

Agrivi
Agrivi is a Croatia based company, providing DST for farmers for simple record keeping, season planning, production analysis, and the possibility to integrate with other technologies of digital agriculture such as weather stations, machinery fleet management, satellite imagery, and others. Agrivi farm management software also provides farmers the possibility to plan their profitability per field and compare planned profitability with actual at the end of the season. The application provides solutions for most crops, even permanent ones. The platform is used in 100 countries, by more than 30.000 clients with Europe and North America providing the bulk of users.

SOYL
SOYL is the leading precision crop production service provider in the UK. SOYL produces and interprets variable rate maps covering over 1 million hectares of land and its software technology is in use in over 15 countries worldwide. Innovative technology, robust data, expert advice and technical support are used to improve growers' economic, agronomic and environmental performance. As pioneers in UK precision farming since 1993 the company is backed by the UK's largest precision farming specific research and development programme.

YARA-Atfarm
Atfarm is a free online service to help farmers manage crop nitrogen and monitor crop biomass using Yara digital tools together with satellite imagery. The application allows farmers to create variable rate application maps for fertiliser application. It uses automatically updated satellite information based on the N-Sensor algorithm, all in an easy-to-use platform. It is also possible to adapt the application map according to individual needs and knowledge of a field. For the analysis of satellite images, Atfarm combines an intuitive and easy-to-use platform with the N-Sensor algorithm, a technology developed by Yara using decades of field trials.

CABI
Fertilizer Optimizer app assists farmers in using fertilisers more efficiently to improve their investment in farming products. The app records information on crops, the area planted, crop market prices and fertiliser costs along with helping farmers budget their investment in fertiliser products. Based on robust crop response functions, it calculates the most profitable combination of fertilisers to purchase and advises site-specific application rates. The app can also consider any integrated soil fertility management (ISFM) practices to tailor the recommendations for a given farm. With this tool, farmers and extension workers can have free access to advice on their mobile devices, with the app able to work offline and produce calculations in the field. The app is currently available for 12 African countries.

Nutrient Expert app
Developed by the International Plant Nutrition Institute (IPNI) the app enables crop advisors and agriculture extension services to obtain fertiliser recommendations tailored to field-specific conditions, which can help farmers increase their yield, market profit and fertiliser efficiency. In addition, the app offers a 'Profit Analysis' module that compares ex-ante profit of a farmer's current practice versus the app's recommendations.

EU initiative, the fastplatform.eu and NAVIGATOR algorithms

In line with the Farm Sustainability Tool for Nutrients foreseen by the new CAP Regulation, the EC's DG Agriculture and Rural Development, the EU Space Programme (DG DEFIS) and the EU ISA2 Programme (DG DIGIT) are supporting the development of the FaST digital service platform (FaST). The FaST platform will

combine data and manual input from farmers to provide customised recommendations on crop fertilisation. Stage 2 of the FaST project will expand the reach of the platform to the farmers of Wallonia (Belgium), Bulgaria, Greece, Romania and Slovakia and it is expected to be completed by the end of May 2022.
Within the framework of the Stage 1 pilots, the ITACyL (Instituto Tecnonlógico Agrario de Castilla y León, Spain) developed **SATIVUM**, a web based nutrient management tool that provides access to farm and parcel information and satellites images.
The Paying Agencies that participated in the first stage of the project (Andalucia, Castilla y Leon, Estonia and Piemonte) will continue to be supported in the running of their platform, throughout the course of Stage 2. (Source: **https://fastplatform.eu/**).

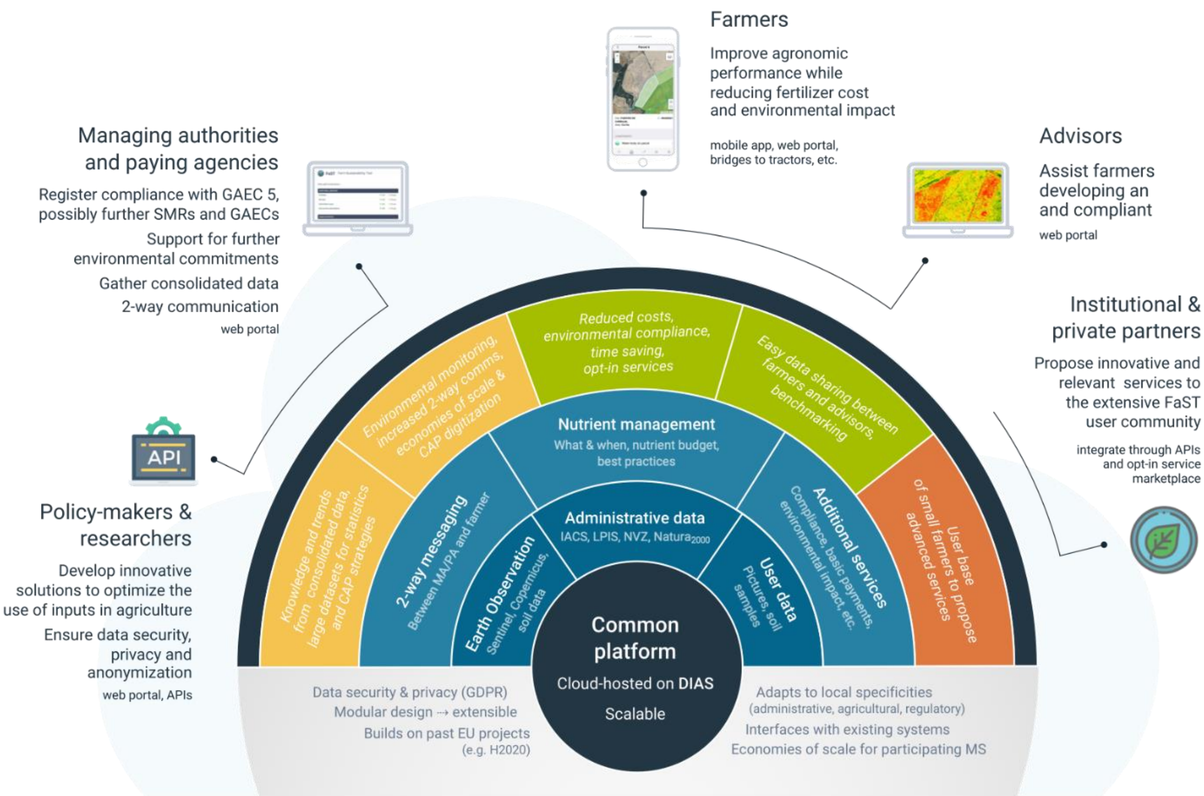

Fig. 5. The concept of the fast platform (Source: https://fastplatform.eu/**)**

This study FaST NAVIGATOR algorithms addresses the availability of nutrient management algorithms adapted to the different characteristics and operational conditions in terms of data availability. These algorithms are necessary for the implementation of the Farm Sustainability Tool for Nutrients in the new CAP. The calculation pathways developed also covered the general equation(s) and sub-models used for the estimation of greenhouse gases emissions and removals, taking advantage of the synergies between the estimation of nutrients and greenhouse gases. Quantitative advice on nutrients and estimation of GHG are accompanied by a module for the assessment of the economic performance of possible alternatives of farm managements on these topics.

3.2 Soil surveying and mapping

Soil sampling and laboratory analysis based nutrient management has a long history, and it is well documented to have served the purpose of nutrient management planning for decades. Traditional soil sampling and survey, if done properly, is still one of the best sources of information for nutrient management planning. Nevertheless, the technological advances in machinery and the need for further optimization, has increased the need for accuracy and density of soil information.

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Different sampling and mapping techniques have evolved over time, many times driven by cost and speed. This resulted in the increasing adoption of proximal soil sensing techniques. Also traditional mapping techniques are slowly disappearing giving more way to both simple (interpolation, kriging) and more advanced (machine learning, etc.) digital soil mapping methods.

A well known and globally used simple soil sample method is the grid based soil sampling. It serves as a base for nutrient management, although the use for commercial within-field soil mapping is questionable, due to its reliability and applicability in heterogeneous soil and environmental conditions. The long tradition and experience of grid sampling can be further developed with decreasing the size of sampled grids to have comparable results to other, more advanced techniques. Nevertheless it would increase the cost of the sampling and analysis.

Directed sampling, or expert knowledge based sampling, may be a good alternative where prior knowledge about soil variability is incorporated into the sampling design, so sampling distribution and intensity is matched with known soil patterns. This methodology can be supported by many digital information on the environment and the soils, such as proximal soil sensing, remote sensing, elevation models, yield mapping, etc., which will be further discussed later in the chapter.

To increase accuracy and decrease the data need of soil maps used for precision agriculture, digital soil mapping (DSM) techniques have evolved in the last decades. DSM is being carried out in many countries and regions on different scale (e.g. Lagacherie and McBratney 2007; Arrouays et al. 2014; Hengl et al. 2014, 2015). Lagacherie et al (2006) defines DSM as 'the creation and population of spatial soil information systems by the use of field and laboratory observational methods coupled with spatial and non-spatial soil inference systems' (Lagacherie et al. 2006). The concept incorporates three main components: the input data, the mathematical/statistical inference system and the resulting spatial information with maps and uncertainty measures (Minasny and McBratney 2016).

3.3 Remote sensing (RS)

Remote sensing is the process of detecting and monitoring the physical characteristics of an object by measuring its reflected and emitted radiation at a distance. This involves an instrument or a sensor mounted on a platform, such as a satellite, an aircraft, an Unmanned Aerial Vehicle, or a probe. The type of information accessible from remote sensing depends on the specific properties of the instrument and its platform (Roy et al., 2002).

In the field of agriculture, the information of interest consists of traits or features of the agricultural systems, and especially how these latter vary in space and time. Nock et al. (2016) defined functional traits that influence organism performance or fitness. The nature of these agronomic traits can be typological, physical, chemical, biological, structural, or geometrical, and can be related to plants or soils. It is important to notice that none of these traits are directly measured by remote sensing instruments. The relationship between what is measured (i.e. radiance) and the traits themselves needs to be somehow modelled in order to infer the later from the former.

Remote sensing has a long history in agriculture as outlined by Becker-Reshef et al. Preliminary research and development on satellite monitoring of agriculture started with the Landsat-1 system (ERTS) in the early 1970s. Already in the early 80s, it was shown by Tucker et al that green vegetation can be monitored through its spectral reflectance properties. Today, a large range of satellite sensors regularly provide us with data covering a wide spectral range (from optical through microwave). Data are acquired from various orbits and in different spatial and temporal resolutions.

A principal difficulty when using RS for soil property characterization is the complexity of soil components and soil spectra. Ben-Dor (2002) stated that soil contains many chemical components including clay minerals, carbonates, OM, water in different states (hygroscopic water, hydration water, and free pore water), salts, etc. Some of these components have strong and distinct spectral signatures (e.g., the clay mineral montmorillonite), and some exhibit weak to non-existent signatures (e.g., quartz and feldspar). Moreover, many of these spectral signatures overlap one another. For example, absorptions at 1.4 and 1.9 μm are common in soil spectra and can be caused by many soil chemical components. Additionally, absorption overlapping may not be a linearly additive process. Finally, agriculture soils are frequently subject to management practices like vehicle traffic that leads to compaction, tillage, and irrigation; each of these affects soil moisture content and aggregate soil particles size, which can have great influence on soil spectra. For these reasons, agricultural soils can exhibit very complex spectra, and characterization of soil properties is difficult (Weiss et al 2020). Although using RS in soil property characterization can be an important aspect in nutrient planning and decision making, most of the solutions available are based on the characterization of the crops/canopy. Some of the most important RS based crop based applications are: crop identification and cropland mapping, crop growth monitoring and yield estimation/prediction, inversion of key biophysical, biochemical and environmental parameters, crop damage/disaster monitoring (Chen et al. 2008)

Satellite based RS

Satellite based RS has been used in agriculture for decades. Many well documented and validated data processing methods are available. The main advantage of the technology is the fast data acquisition, which means large areas are covered with one image, although as a disadvantage these are not as frequent in time and might not be taken exactly at the time needed. A large advantage is the availability at no cost through the Sentinel and LandSAT programs, from the European Space Agency and the United States Geological Survey respectively.

The spectral bands, resolution and revisit time are different for the platforms (16 days and 10 days respectively), but with the combination of the images, a 2.3 days global median average of revisit intervals can be achieved (combination of four sensors from Sentinel 2 and Landsat 8 and 9), which serves global agriculture greatly.

Satellite based RS is used for several purposes in agriculture such as monitoring soil properties, crop conditions, estimate biomass production of any given region, and monitoring tillage activities. The correlation between plant Nitrogen status and several RS based vegetation indexes have been proved in numerous studies. The Sentinel red-edge technology has been proven especially important in agriculture related applications, not only due to the innovation in this wavelength but also the due to the ground resolution (Clevers and Gitelson, 2013, Gonzalez-Piqueras et al 2017). Since N status depends on many different variables, RS should not be the only data input when planning N applications though.

It enables stakeholders to determine land usage, harvests prediction, observing changes in season, and, most importantly, helping in proposing and implementing a financially and ecologically viable sustainability development policy. Several solutions are available in which RS data is incorporated into mathematical models to calculate the probabilities and determine how much yield is expected at the time of harvesting. More advanced and complex technologies can identify potential threats to the crops (web14).

Unmanned Aerial Vehicles (UAVs)

UAVs became common in the last couple of years for farm management. With the decrease of prices and the advancement of the technology, more and more farmers are taking advantage of this technology at different levels. In particular, a lot of research effort is put into the UAV based RS systems to simplify the data processing workflows, and provide off-the-shelf solutions for farmers. Its main advantage over the Satellite based RS is that the ground resolution is much better (a 3 cm ground resolution can easily be achieved compared to the Sentinel's 10 m ground resolution), thus it provides more information on the fields and crops and serves site specific nutrient application better. Another potential advantage is its readiness, which comes in handy when clouds difficult the acquisition of satellite based images, and RS data is needed instantly.

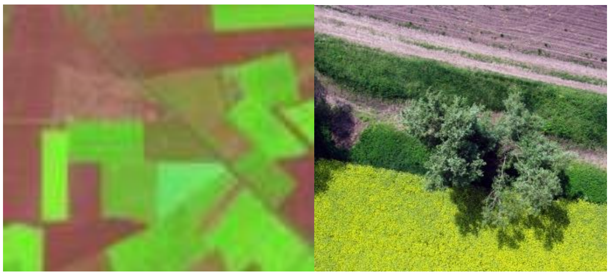

Fig. 6 Spatial resolution comparison of Satellite (LandSat 7.) and UAV based images

Nitrogen-sensors

N sensors were developed to provide on-the-go sensing and direct control of site specific Nitrogen applications. The scientific background is similar to Satellite or UAV based RS techniques. Near Infra-Red, Red Edge, Red or similar reflectance ranges are sensed, processed and translated into controlling tasks, mainly using plant biomass or Nitrogen status. Many of these tools are 'black box' solutions (Yara Nsensor, AgLeader OptRX), and no information about them is available other than the basic scientific background. The advantage of the tools is the readiness and the direct control, which does not require post processing on computers in different software. This technology comes with a higher cost compared to the previously described tools.

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3.4 Proximal soil sensing

Proximal soil (PS) sensing is also a remote sensing technology, but it is discussed separately in many cases. It is a technique which is currently intensively used in precision agriculture and soil survey to provide fast and accurate information for nutrient management and variable rate applications based on certain measured properties. These methods offer great opportunities for cost-efficient collection of measurement data with extensive spatial coverage. Different techniques have evolved and are currently in use globally, such as electrical, electromagnetic, gravity, ground-penetrating radar, magnetic, seismic, self-potential, etc. The three most commonly used geophysical methods in soils and agriculture are electromagnetic induction (EMI), electrical resistivity (ER), and ground-penetrating radar (GPR). A large array of agriculturally important soil properties (including textures, organic and inorganic carbon content, macro- and micro-nutrients, moisture content, cation exchange capacity, electrical conductivity, pH, and iron) were quantified with PS and RS successfully to the various extents. Applications vary from laboratory analysis of soil samples with a bench-top spectrometer to field-scale soil mapping with various on-the-go sensors. The measures of soil properties are the basis of many nutrient management applications and solutions, thus the quick sensing technology can serve as an alternative to wet chemistry methods and therefore fasten decision support.

Agrocares PS technology:

Provides a solution to scan the nutrients in soil, feed or leaf with an easy-to-use handheld tool. Information about the nutrient status on the soil /feed is available on a smartphone within minutes, through a deep learning database and the nutritional database of Trouw Nutrition.

3.5 Other data sources and techniques

Besides the previously described most common techniques and technologies, many more are available and many times just as important. The number of these tools is constantly growing so it is difficult to discuss all of them. Some techniques which has been used successfully for many years in site specific application include:

Digital Elevation Models (DEMs):

In many cases DEMs are very well correlating with yield maps, or yield potential within the field, due to its correlation with soil moisture availability of soils. It has been demonstrated that quality DEMs can serve site specific applications of nutrients and seeds with great success. For these purposes, quality products are necessary, especially where micro-relief drives soil productivity. The source of DEMs can be diverse: from radar based remote sensing, UAV based 3D reconstruction or GPS equipped farm machinery (especially if Real-Time Kinematic (RTK) positioning is available through base stations or other correction data). It is an easily accessible source, and it is getting less attention than it deserves.

Yield mapping

Yield maps are one of the main data sources of Precision Agriculture and nutrient management planning. These maps not only represent the yield potential of fields, but also provide information on profitability, and serve as a great base for nutrient planning. However, it is an expensive technology.

Yield maps are based on different technologies, depending on the producer, but all are designed to map the actual yield with high spatial resolution and, in many cases, the soil moisture and other parameters. Disadvantage of the technology is the high rate of poor-quality data. Some research shows that up to 60% of measurements can be unreliable and must be discarded for further analysis. There are different reasons, such as yield map smoothing errors; unknown crop width entering the header during harvest; time lag of grain through the threshing mechanism; positional errors; surging grain through the combine transport system; voids (empty spaces) and others. Another disadvantage is the lack of further information on the cause of harvested yield, such as low yields due to water ponding, or wildlife damage and other. These, without further information, such as ground truthing or RS can lead to nutrient management plans not representing the actual conditions.

3.6 Precision agriculture (PA) as a tool for sustainable nutrient management

Precision Agriculture is a management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability. This results in an improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production (ISPAG, 2019).

Precision agriculture focusses on improving nutrient use efficiency at the appropriate scale requiring appropriate decision support systems (e.g. digital prescription maps) and equipment capable of varying application at these different scales. Therefore Precision Agriculture, or site specific applications, can be a key technology to properly apply the plans provided by the digital tools for nutrient management. Modern fertilisers and sprayers are equipped with GPS based systems to perform accurate and site specific applications suitable for any farm size. It has the potential to improve production and nutrient use efficiency, ensuring that nutrients do not leach from or accumulate in excessive concentrations in parts of the field, which creates environmental problems.

Market development expectations for Precision Agriculture

Increasing awareness about the benefits of precision agriculture, in optimizing agricultural production, has resulted in a great boom in the precision agriculture market. The global precision farming software market is anticipated to register a compound annual growth rate of 16.7% during the next period (2021-2026).

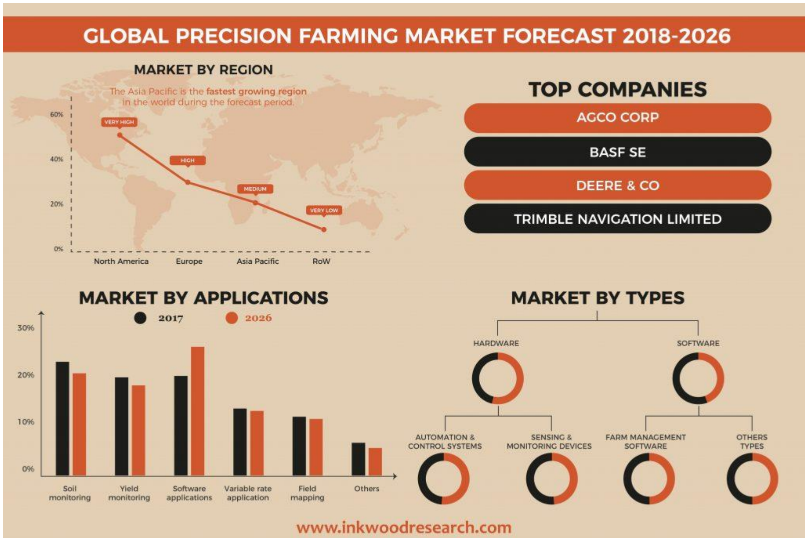

Fig. 7. Source: inkwoodresearch.com (https://inkwoodresearch.com/reports/precision-farming-market/**)**

The advancements and innovations in technology are the major factors driving the precision agriculture market, helping the farmers maximize their yield and minimize losses with efficient use of resources. North America is the largest and more mature market for precision agriculture, followed by Europe. Together, these two regions constitute more than 50.0% of the global precision agriculture software market.

3.7 Which tools for which cases/needs?

As presented in the previous sections, many different technologies, tools and techniques exist and are available to farmers to support decision making and assist optimized nutrient management. Although these tools are widely available in most of the EU countries, a widespread comparison of these tools, in terms of accuracy and suitability under different climatic, soil and environmental regions, hardly exists or is known by farmers. Such a guideline would be necessary to support farmers when choosing the best available technologies as well as to properly address soil nutrient management based on environmental and managerial issues.

In that sense the Horizon2020 Fairway project reviewed approaches for protecting drinking water from nitrate and pesticide pollution. A comprehensive assessment of decision support tools (DSTs) used by farmers, advisors, water managers and policy makers across the European Union as an aid to meeting CAP objectives and targets was undertaken. It encompassed paper-based guidelines, farm-level and catchment level software and complex research models. In the project more than 150 DSTs were identified, out of which 36 were selected for further investigation. The majority of the selected DSTs were farm management tools and were included under the assumption that smart use of nutrients/pesticides indirectly improves water quality by reducing losses to the water environment. Only three of the selected DSTs were explicitly developed to consider the impact of mitigation methods on water quality (Nicholson et al. 2020).
As demonstrated through the findings of the EIP-AGRI Operational Group on 'Development of a cost-optimized novel soil sampling methodology for precision agriculture' from Hungary, the available survey tools can provide different basic information which will result in different decisions and application strategies, not all of them suitable under the assessed conditions and farm technologies. The demonstrated methods were provided by different PA consultants along with the fertilizer application plans.

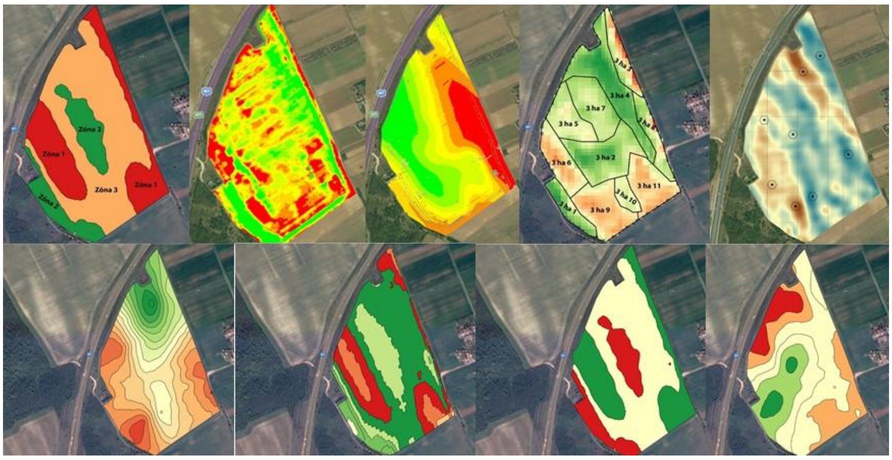

Fig.8. Different survey and data collection methods applied on the same field: Top row: Electro Magnetic scanning and clustering, Yield map, DEM, 3 years mean NDVI (Sentinel), Electrical conductivity scanning. Bottom row: Phosphorus application plans based on the following base information: grid soil sampling, EM scanning (provider 1 and 2), EC scanning.

Results showed that with the usage of unreliable basic information, the nutrient technology will be underperforming and might generate more issues for soil, water and air pollution, than the previous technologies. There is a growing need for standardization and validation with both the increasing number of tools and the uptake level of these methods.

3.8 Barriers for tool uptake by the farmers

Although market trends and farm machinery sales indicate that smart farming uptake is increasing, it is still low. In addition, there are big differences within the European farming community in terms of digital uptake. This diversity may depend on the region (some regions are front runners while others lack behind), sector (some sectors are more digitized, i.e. intensive horticulture), generation, farm size, etc. The combination of all these variables defines a range of farmer 'digital profile' and therefore of farm information needs.

Despite the fact that many of these technologies, especially the smart farming equipment, were more commonly used among large farms, with the technological advancement and the increasing competition among technology providers, technology prices have decreased. In addition, new machines are not always necessary to start smart applications, due to the upgrade kits available at different producers. This shows that in many countries financial barriers might not be the most common ones.

On the contrary, many farmers still need support to understand and take up new technologies and to make decisions on ICT use adapted to their specific needs. They may also need support to find out about and

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understand the digital-based solutions on offer and making the right choices for their farm. In that sense, many technologies are already available, but a lack of awareness, training and education of farmers, and in some cases of advisers, hinder their adoption. Besides, farmers do not see clearly what the return on investment (ROI) is when it comes to their specific situation. In that sense it is frequently acknowledged that there is still wide room for improvement of tools in terms of e.g.: user-friendliness, inter-operability, accuracy and relevance of the output, etc. Cost/benefit analysis are not available in many cases. At the same time, for some tools and technologies, basic infrastructures needed for operation are not in place, either at farm level (i.e. particular equipment) or in the area (i.e. no bandwidth or connectivity at all).

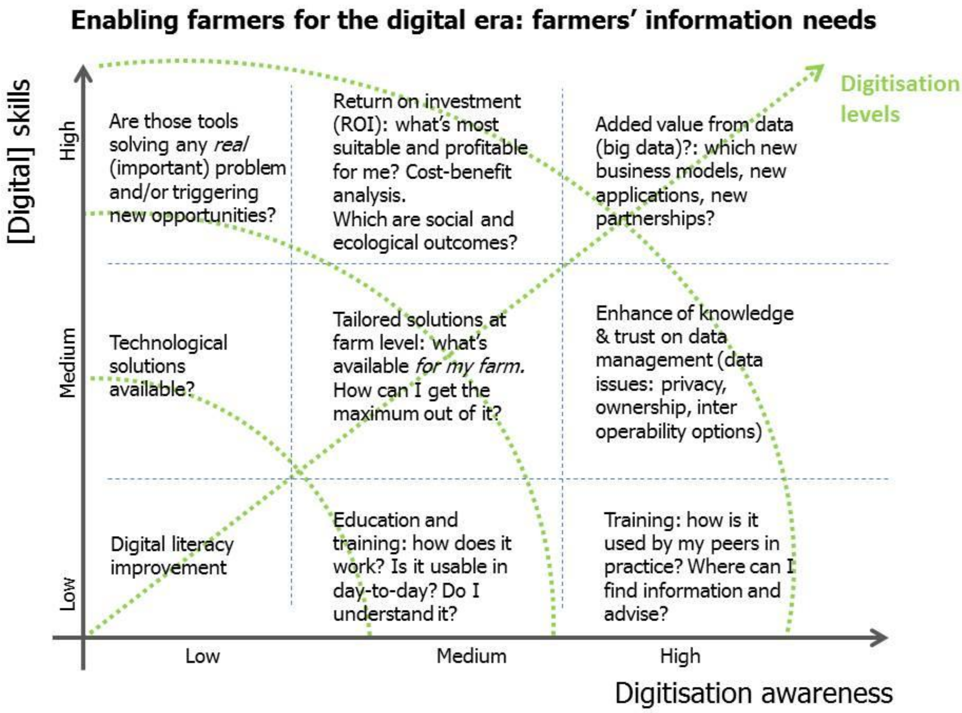

Fig. 9. Farmers' information needs according to awareness and skills levels (EC, 2018)

On a different level, those who are already aware of technologies and the opportunities they offer, may lack of trust, confidence or certainty about how and by whom the data will be used. Finally, getting extra added value from the use of those data poses some challenges and needs. For instance, some farmers could play a significant role during the development of new business models, applications, etc., but most of them lack the skills and/or the position within the ecosystem to get involved and directly benefit from that possibility.

In summary, barriers behind the low uptake level in the EU vary by region, but there are frequent ones such as:

- Lack of knowledge of and/or trust (including privacy and data protection concerns) on digital technologies
- Lack of computer literacy (at the management or lower employee levels)
- Lack of motivation for change
- Available technological solutions not addressing actual challenges and farmer needs or tools underperform
- Low ROI or/and no information on cost/benefit
- Financial barriers (expensive machinery and equipment)
- Technology dependency (i.e. solutions linked to full technological packages (all-in) not flexible to adapt to farm diversity)
- Farm or field size less suitable or attractive for smart solutions
- Lack of technological infrastructure, especially insufficient connectivity

4. Nutrient management and the environment

In the last century, human-made fertilisers have greatly boosted crop production, letting farmers grow more food on less land. But this increase in fertiliser use has come at a cost in the form of water, air, and soil pollution, greenhouse gas emissions and human health issues.

Water

Farmers apply nutrients on their fields in the form of chemical fertilisers and animal manure, which provide crops with the nitrogen and phosphorus necessary to grow and produce. However, when nitrogen and phosphorus are not fully utilized by the growing plants, they can be lost from the farm fields and negatively impact air and downstream water quality. This excess nitrogen and phosphorus can be washed from farm fields and into waterways during rain events and when snow melts and can also leach through the soil and into groundwater over time. High levels of nitrogen and phosphorus can cause eutrophication of water bodies. Eutrophication can lead to hypoxia ("dead zones"), causing fish kills and a decrease in aquatic life. Excess nutrients can cause harmful algal blooms (HABs) in freshwater systems, which not only disrupt wildlife but can also produce toxins harmful to humans.

For EU27+UK, between the reporting periods 2008-2011 and 2012-2015, both net nitrogen and phosphate balance slightly increased at EU-28 level from 31.8 to 32.5 kg N/ha and from 1.8 to 2.0 kg P/ha respectively. For the 2016-2019 period, the N balances are higher than 100kg/ha for Belgium, Cyprus, Luxembourg and the Netherlands. Phosphate balances are higher than 20kg/ha for Cyprus, Ireland, and Malta. Since 2008, for those Member States showing high nutrient surplus, the only decrease was observed in Malta regarding the phosphate balance. In 2016–2019, 14.1% of groundwater stations still exceeded in annual average 50 mg nitrates per litre, a situation comparable to the previous reporting period, in which 13.2% stations exceeded 50 mg/l. As regards surface waters, at EU level, 36% of rivers and 32% of lakes, 31% of coastal and 32% of transitional water and 81% of marine waters were reported as eutrophic (EC, 2021).

Basu et al (2010) discovered that nitrogen is building up in soils, creating a long-term source of nitrate pollution in ground and surface waters. Once Nitrogen is being stored in the soil, it can still be a source of elevated nitrate levels long after fertilisers are no longer being applied. They analyzed long-term data from over two thousand soil samples throughout the Mississippi River Basin to reveal a systematic accumulation of nitrogen in agricultural soils. In many areas, this accumulation was not apparent in the upper plow layer, but instead was found from 25-100 cm beneath the soil surface. This accumulation is a result of not only fertiliser applications but the increases in soybean cultivation and changes in tillage practices over the past 80 years. Their modeling results suggest that this nitrogen legacy could still be leaching into waterways more than three decades after nitrogen is no longer being applied to fields.

According to Goyette et al. (2016) the maximum amount of nutrients which can accumulate in a watershed has a critical threshold at 2.1 tons per square kilometer of land. Beyond this limit, additional inflows into watersheds cause a marked acceleration of the nutrient in the runoff. This amount is extremely low, according to the researchers. Indeed, given the current rate of nutrient use around the world, this saturation threshold could be reached in some cases in less than a decade. In the case of phosphorus, the earth absorbs it year after year and, in the long term, its absorption capacity is reduced. That's when historical phosphorus inputs contribute more to what reaches the waters.

Air and climate

Fertilised soils, as well as livestock operations, are also vulnerable to nutrient losses to the air. Nitrogen can be lost from farm fields in the form of gaseous, nitrogen-based compounds, like ammonia and nitrogen oxides. Worldwide, agriculture is the second-largest source of climate change causing pollution—and both the manufacturing and application of fertiliser has a heavy emissions toll (web15).

Emissions from farms outweigh all other human sources of fine-particulate air pollution in much of the United States, Europe, Russia and China. Fumes from nitrogen-rich fertilisers and animal waste combines with pollutants from combustion—mainly nitrogen oxides and sulfates from vehicles, power plants and industrial processes—to create tiny solid particles, or aerosols, no more than 2.5 micrometers across, about 1/30 the width of a human hair. Aerosols can penetrate deep into lungs, causing heart or pulmonary disease.

Lelieveld et al (2015) estimates they cause at least 3.3 million deaths each year globally. Many regional studies have shown agricultural pollution to be a prime source of fine-particulate precursors, but Bauer et al (2016) is one of the first to look at the phenomenon worldwide and to project future trends. The study's results show more than half the aerosols in much of the eastern and central United States come from farming. Some fertilisers need to be produced on high pressure under high temperatures thus taking a lot of energy to manufacture. Most of that energy comes from burning fossil fuels like coal and methane gas, which releases the greenhouse gas carbon dioxide, the main cause of climate change. Ammonia manufacturing today contributes between 1 and 2 per cent of worldwide carbon dioxide emissions. Fertilisers also produce greenhouse gases after farmers apply them to their fields. Crops only take up, on average, about half of the nitrogen they get from fertilisers. Although nitrous oxide accounts for only a small fraction of worldwide greenhouse gas emissions, nitrous oxide warms the planet 300 times as much as carbon dioxide (web15).

There are many ways that farmers can reduce nutrient losses from their operations, including, but not limited to:

- Using Conservation Drainage Practices
- Ensuring Year-Round Ground Cover
- Planting Field Buffers
- Implementing Conservation Tillage
- Managing Livestock Access to Streams
- **Adopting Nutrient Management Techniques: Farmers can improve nutrient management practices by applying nutrients (fertiliser and manure) in the right amount, at the right time of year, with the right method and with the right placement**

Towards more comprehensive digital tools for nutrient management?

The 4R's of nutrient management (web16) is a practical example that addresses reducing the nutrient loss to the environment, and the related harmful effects. The 4R's stand for right source, right rate, right time, and right place and serve to guide farmers to the management practices that help keep nutrients on and in the field. In that sense implementation of the 4R's aims to align the economic and environmental components of nutrient management, but it demands the simultaneous consideration of multiple aspects (and variables) and therefore a more holistic nutrient management approach. Each of the components of the 4R's could be supported by different digital tools, thus helping to achieve a more comprehensive nutrient application to enhance environmental performance.

The Nutrient Stewardship 4R Pocket Guide (web16) explains the 4R's as follows:

The first R is **Right Source**:

- Are the fertilizer nutrients being used (commercial or manure) available for immediate or delayed crop uptake?
- Is there a combination of fertilizers that can be utilized best?
- What nutrients are already available in the soil?

The next R is **Right Rate**:

- Match amount of fertilizer applied to the crop nutrient uptake
- What is the crop nutrient demand?
- Perform a soil analysis (manure analysis as well if using this as the fertilizer source) to appropriately match the amount of fertilizer needed for crops based on individual field fertility
- Make sure equipment being used to spread the fertilizer or manure is calibrated properly for appropriate distribution
- Consider crop yield goals
- Consider the law of diminishing returns: the unit of nutrient applied - crop yield increase generated

The third R is **Right Time:**

- Plan for fertilizer nutrients to be available during crop demand – many times this is close to planting

- Consider the weather and seasonal conditions:
    - Potentially more nutrient runoff during the winter
    - Saturated fields are unable to retain nutrients effectively
    - Application of fertilizer immediately before a large rainfall could contribute to nutrient runoff

Lastly, determine the **Right Place:**
- Place fertilizer in the root zone, where crops can successfully access the nutrients
- Consider the management practices for each field based on the following:
    - Crop being grown
    - Soil type
    - Slope
    - Distance to surface waters
    - Soil characteristics (can differ throughout the field) like nutrient supply capacity and the vulnerability to nutrient loss
    - Phosphorus or P-Index
    - Potentially incorporate GPS and variable rate seeding data

Considering them in an integrated way, all those variables entail more sophisticated and complex tools, as well as the need for more data and, eventually, the increase of the technical knowledge required for their operation. Some questions arise: how to find a balance between the comprehensive approach and the operational feasibility? Are there critical aspects to concentrate on, while respecting the environmental ambition –at same level than the economic one-? Which are they? How to keep the tools simple enough to facilitate a wide uptake?
In addition, as tools become more comprehensive, the odds increase that they contribute to other functions, besides nutrient management. For instance, some of the nutrient management tools available in the market are indeed crop management tools and aim to support the broader crop operations planning. But they frequently have a narrow approach focusing on few technical aspects, even lacking the economic dimension, and do not address many of the aspects more relevant from an environmental perspective as mentioned in the 4Rs example.
So, are digital tools for nutrient management actually an opportunity to speed up farmers' uptake of digital solutions going beyond the sphere of nutrient management? If so, could those digital tools be the basis, for instance, for applications for precision irrigation, pest management, assessment of GHG emissions and removals (i.e. Carbon Farming), among others? Which ones seem to be more feasible? Where are the most promising trade-offs? Who could benefit from them? What else is needed to progress towards those new uses and functions (for instance in terms of data, tool inter-operability, technological environment, farmer or advisor skills)? Or, on the contrary, would that –even more- complex tools loose the focus and therefore the usefulness at farm level?

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