NutriBudget

Optimisation of nutrient budget in agriculture

D3.1 Overview of existing indicators used in national and European policies and market initiatives in relation to agronomic and environmental aims

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Preface

The NutriBudget project aims to develop and implement a prototype of an integrated nutrient management platform in various regions across Europe, as a decision support tool (DST) for farmers, advisors, European policy makers and regional authorities. The development of the NutriPlatform will be based on knowledge from existing and new field-tested agronomic mitigation measures linked to advanced NutriModels, which integrate various nutrient models, common data standards and relevant monitoring indicators. Thereby, NutriBudget will contribute to systemically optimize nutrient flows and budgets across different agricultural production systems and regions in the EU to limit and reduce pollution due to excessive use of nutrients and nutrient losses in the environment. The NutriModels will be able to operate at different scales: for farmers at the farm level and for regional authorities and policy makers at the regional to EU level, taking into account a holistic, sustainable and data-driven perspective on agriculture, linking the flow of nutrients between soil, water, air, plants, animals, feed and food with specific validated technological or nature-based mitigation measures within a financially viable transition route towards the desired nutrient status, as described in the Zero Pollution Action Plan and the Farm to Fork Strategy.

To assess the actual farm performance in view of agronomic and environmental targets, an integrative key performance indicator (KPI) framework will be designed to monitor the transition from the current to the desired status to have optimised farming systems (conventional, agro-ecological and organic in animal and crop production) in equilibrium with maximum agricultural performance and minimal environmental pressure. As such, this framework will guide the actual decision support as well the identification of appropriate roadmaps to reach the desired status for soil surpluses of carbon and nutrients in view of targets for soil quality, water quality, climate, biodiversity and crop production.

This report describes the design of a framework that integrates agri-environmental indicators and productivity metrics into a comprehensive set of critical performance indicators reflecting farm performance on both environmental and agronomic aspects (Task 3.1). It includes the selection of indicators, the integration of indices in relation to multiple targets (for carbon and nutrient budgets, and accounting for synergies and trade-offs) as well as possible additional impacts on environment. To do so, an inventory of existing assessment schemes for agricultural sustainability across Europe and private tools in use has been done, and the identified tools were evaluated in view of their potential to assess the farm sustainability for the five aforementioned targets. These insights led to the design of an integrative NutriKPI framework that will guide the further model design, evaluation and assessment of measures evaluated.

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Executive Summary

To meet the demands of a growing population, a high productive agriculture is required now and in the future. This has impacts on crop growth, soil and environmental quality. Given the large heterogeneity in agricultural production systems across Europe, developing strategies to balance environmental and production targets requires spatially explicit information on i) safe nutrient losses to minimize environmental risks while improving soil health, ii) the potential to enhance crop production by optimizing inputs on existing agricultural land, and iii) the nutrient use efficiency at which both environmental and crop production objectives can be met. The development and implementation of integrative Key Performance Indicator (KPI) frameworks are essential to evaluate the effectiveness of agricultural policies and farm strategies in view of the desired agronomic and environmental objectives. KPIs serve a crucial role in agri-environmental policy and farm strategies by simplifying, quantifying, and conveying information related to environmental conditions, as well as the various aspects of farming, such as inputs, outputs, yields, and economic performance.

The NutriBudget project aims to develop and implement a prototype of an integrated nutrient management platform, called NutriPlatform, in various regions across Europe, as a decision-support tool (DST) for farmers, advisors, European policymakers and regional authorities. The current report (*D3.1 Overview of existing indicators used in national and European policies and market initiatives in relation to agronomic and environmental aims*) describes the development of an integrative KPI framework of agronomic and environmental indicators to monitor the transition from the current to the desired status, in order to obtain optimized farming systems (conventional, agro-ecological, and organic in animal and crop production) in equilibrium with optimal agricultural performance and minimal environmental pressure.

The NutriKPI framework builds upon an inventory and assessment of existing assessment schemes for agricultural sustainability across Europe and other market initiatives (Chapter 3). More than 32 existing schemes and tools are described and evaluated (Chapter 4). The common quantification methods as well as the indicators used are integrated in a NutriKPI framework guiding the objective of the NutriBudget approach (Chapter 5). We selected carbon and soil nutrient surpluses (being broadly applicable across spatial scales and farming systems) as relevant effect indicators. Critical threshold values can be derived in view of their impact on crop and animal production (and thereby farm economics), water quality, climate change mitigation and biodiversity. The NutriKPI framework can support the evaluation of farm performance in view of the long-term objective to make agriculture more sustainable. In that respect, it is a powerful tool that can be combined with the mean-based indicators (proxies for the desired environmental conditions and more practical to measure at the farm level like i.e. cultivation of catch crops), the measures selected from the measurement catalogue (WP1) and models outputs that take into account spatial variations (WP2). In general, the main conclusions and findings of D3.1 are the following:

- We performed a **comprehensive evaluation of key performance indicators** being used in 32 existing tools across Europe where we assessed their scientific value, their applicability, data needs, and relevance in view of the desired targets for soil health, crop yield, water quality, biodiversity, and climate.
- We **selected relevant KPIs** that are needed to reach the overall objective of the Nutribudget project aiming to "*systematically optimize nutrient flow and budget across different agricultural production systems and regions in the EU to limit and reduce pollution due to the excessive use of nutrients and nutrient losses to the environment*". We evaluated the value of means or effect bases indicators in view of farmers perspective to contribute to a farming system with lower nutrient inputs and associated environmental impacts.
- We **identified missing gaps** for the existing KPIs and proposed a **methodology to derive critical targets and thresholds** for carbon and nutrient surpluses (for nitrogen, phosphorus, cations and metals) to derive spatial explicit KPIs to be used for all farming systems across Europe.

- We **developed an integrative NutriKPI framework** that integrates agro-environmental indicators and productivity metrics into a comprehensive set of critical performance indicators reflecting farm performance on both environmental and agronomic aspects. It includes the selection of indicators, the integration of indices in relation to multiple targets (for carbon and nutrient budgets, and accounting for synergies and trade-offs) as well as possible additional impacts on environment.

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List of Abbreviations

C	Carbon
CEC	Cation Exchange Capacity
DPSIR	Driver-Pressure-State-Impact-Response
DST	Decision Support Tool
ESI	Environmental Sustainability Index
ESS	Ecosystem Services
EU	European Union
GHG	Greenhouse Gasses
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
N	Nitrogen
P	Phosphorus
SDG	Sustainable Development Goals
SOC	Soil Organic Carbon

1. Introduction

1.1 The challenge

To meet the demands of a growing population, agriculture continues to intensify, along with increasing and evolving impacts on crop growth, soil and environmental quality (Kanianska, 2016). There has been a great increase in world food production since the 1960s, with a 68% increase in Europe over 40 years and an increase in per capita agricultural production, accompanied by a likewise increase in machinery and fertilizer use (Pretty, 2008). Increased inputs of nitrogen (N) and phosphorus (P) to the soil have also led to substantial negative impacts on biodiversity, drinking and surface water quality, and human health (Amery & Schoumans, 2014; Cordell et al., 2009; European Commission, 2013; Kros, et al., 2015; Tonitto et al., 2006; Velthof et al., 2014). Only 60% of the N applied to agricultural land in Europe is taken up by crops, while the remainder is lost to the environment (Leip et al., 2013).

Since the 1990s, the N use efficiency (NUE) has increased (Van Grinsven et al., 2013) but by far not enough to reduce N losses sufficiently to meet environmental targets. Nitrogen that is lost to the environment leads to unwanted side-effects including: (i) ammonia emission, causing nutrient enrichment and decreases in plant species diversity through redeposition onto terrestrial ecosystems (e.g., Spranger et al., 2008; De Vries et al., 2010) and affecting air quality by contributing to particulate matter (e.g., Pozzer et al., 2017); (ii) N runoff, causing eutrophication of surface waters (e.g., Camargo and Alonso, 2006); (iii) nitrate leaching to groundwater, causing degradation in water quality (e.g., Powlson et al., 2008; van Grinsven et al., 2006) and (iv) nitrous oxide emissions, contributing to climate change (e.g., Freibauer & Kaltschmitt, 2003). In addition, there are indications for a decline in soil organic carbon (SOC) content in response to climate change (Wiesmeier et al., 2016), which is defined as a threat for European soils due to its crucial link with ecosystem functioning (Haddaway et al., 2014; Lugato et al., 2014; Stolte et al., 2016). Agriculture is challenged to intensify sustainably in order to meet the demands of improving yields in a changing climate without compromising environmental integrity or public health.

Carbon and nutrient inputs play a key role in crop production and raising livestock for food security, human nutrition and other uses in the bio-economy. In 2020 the scientific panel on Responsible Plant Nutrition came with 'a new paradigm for plant nutrition' to facilitate the transition to a new global food system in which multiple socioeconomic, environmental and health objectives must be achieved (Dobermann et al., 2022). The new nutrient economy will become an integral component of a low carbon emission, environment-friendly and circular economy, supporting the food and nutrition requirements of a rising global population and improving the income and livelihood of farmers worldwide. A sustainable farming system aims therefore to

- improve farm income,
- increase nutrient recovery and recycling from wastes,
- improve and sustain soil health,
- enhance human nutrition and health through nutrition-sensitive agriculture,
- minimize greenhouse gas emissions, nutrient pollution and biodiversity loss, and
- be climate resilient.

Given the state of the art of current agronomic knowledge, Dobermann et al. (2022) addressed several key questions that need to be resolved in the coming 20 years in order to facilitate the transition to a more sustainable food system. Most of these are highly interlinked with the optimization of nutrient budgets in primary production as well with the approach highlighted in NutriBudget. The current knowledge gaps include the derivation of region specific roadmaps for fertilizer use and nutrient use efficiency (to optimize budgets over space and time), the selection of agronomic measures to boost high nutritional crop production, the need for data-driven technologies and policies to accelerate the adoption of precise nutrient management solutions, the design of measures that improve soil health and related resilience of farming systems to extreme climatic events, and innovative technologies to monitor nutrients and implement high levels of sustainability stewardship.

1.2 Optimizing farm performance

Sustainable agricultural production refers to strategies for increasing food production on existing agricultural land while minimizing environmental impacts. These strategies include fertilizer, crop and soil management (Young et al., 2019; 2021). Increasing agricultural output can be achieved in two ways: by increasing agricultural area (land expansion) or by enhancing productivity to close yield gaps on existing lands (land intensification) (Tilman et al., 2011). Land expansion often increases greenhouse gas emissions and negatively affects biodiversity and ecosystem services, and is challenging as suitable land is increasingly scarce (Lambin et al., 2013). The area of agricultural land will decline the next decade from 161.9 M ha to 160.5 M ha. This reduction is due to lower yields making production on marginal land less attractive, combined with a lack of generational renewal in remote rural areas and competition for land with forest and urban areas due to reforestation (EU agricultural outlook 2021-31: lower demand for feed to impact arable crops (europa.eu)). Closing yield gaps, on the other hand, usually requires increasing inputs, such as water, N and other nutrients that may counteract the efforts made to reduce N pollution and also negatively affect biodiversity and a wide set of ecosystem services.. The challenge therefore is to maintain or even increase food production while remaining within safe thresholds for environmental quality. To enhance the sustainability of agriculture by management, it is key that we understand the management impact on crop growth, soil health and environmental quality. Because impacts vary by agroecological conditions (Young et al., 2021), successful management strategies should be tailored to site properties, as illustrated for selenium by Ros et al. (2016). Furthermore, various synergies and trade-offs among management practices and sustainability indicators exist (Klapwijk et al., 2014). When only single impacts are considered, this can lead to unexpected outcomes in relation to the other aspects that a management measure affects.

Given the large heterogeneity in agricultural production systems (within and between the systems) across Europe, developing strategies to balance environmental and production targets requires spatially explicit information on i) safe nutrient losses to minimize environmental risks while improving soil health, ii) the potential to enhance crop production by optimizing inputs on existing agricultural land, and iii) the nutrient use efficiency at which both environmental and crop production objectives can be met. Spatial variability among and within farming systems should therefore be considered when optimizing carbon and nutrient budgets. Considerable effort in the past decade has been directed to enhancing our understanding of the role of soil properties and/or landscape attributes on soil carbon and nutrient dynamics and crop response. Application of the existing research is still lacking in the daily farm management, as the gap between research and farmers is too wide. In daily farm management, the focus is mostly on crop and nutrient management by estimation, and farmers tend to neglect the management or lack the knowledge for the proper management of soil fertility on the long term. In addition, social and economic drivers controlling soil and nutrient management are usually not included in research-oriented studies whereas these factors evidently affect farmer's decisions on their day-to-day management. Hence, there is a strong need of integration of environmental, social and economic aspects of soil and nutrient management (both in the short and long term) in simple tools easily accessible for the agricultural community.

Numerous strategies have been implemented to address environmental challenges arising from agricultural practices and to rejuvenate deteriorated ecosystems (Eyhorn et al., 2019). In Europe, these strategies typically involve land management measures aimed at achieving desired outcomes. These measures include specifications on livestock grazing limits, constraints on fertilizer and pesticide usage, and the establishment and maintenance of grass and biodiversity buffer strips around arable fields (Kleijn et al., 2020). Such policies have encountered several limitations, including:

- Stakeholder Engagement: One of the primary shortcomings is the inadequate inclusion of relevant stakeholders in decision-making process, especially in the formulation of land management measures. Farmers, who possess valuable local expertise, are often excluded from the decision-making process. This omission can lead to the ineffective implementation of prescribed strategies and a lack of motivation among farmers to adopt sustainable farming practices (Atela et al., 2015; Baynes et al., 2021).
- Single-Issue Focus: Another issue with current policies is their tendency to address sustainability challenges as isolated problems, optimizing solutions for specific environmental

aspects. This narrow, single-issue approach can result in positive outcomes in one area while inadvertently causing neutral or negative effects in others. For instance, a policy aimed at reducing ammonia emissions to mitigate eutrophication may unintentionally contribute to climate change by promoting N_2O (Berkhout et al., 2019; Moerkerken & Smit, 2016).

- Local Focus and Benchmarking: Many existing programs tend to focus narrowly on improving the local agricultural situation, benchmarking farmers against themselves or their peers (e.g., demanding reductions in fertilizer or pesticide usage). However, they often neglect to assess whether these measures collectively add up to make a significant impact on a landscape or ecosystem scale. Consequently, even if every farmer adheres to the prescribed measures, the restoration of biodiversity and ecosystem functions at a larger scale is not guaranteed (Kleijn et al., 2020).
- Supply Chain Stakeholders. The management of crops, water, nutrients and pesticides is often dependent on farm advisors (with or without product recommendations) or contract requirements from partners in the supply chain (e.g. fixed delivery dates for potatoes or sugar beets) that overrule the underlying motivation behind the policies implemented.

In view of these limitations, the development and implementation of more comprehensive and inclusive KPI frameworks are essential to evaluate the effectiveness of agricultural policies. Such frameworks should consider the multifaceted nature of environmental challenges, engage local stakeholders, and assess the collective impact of measures on a broader landscape and ecosystem scale. This holistic approach is critical to ensuring the long-term sustainability of agricultural practices and the restoration of degraded environmental systems.

1.3 The value of decision support and Key Performance Indicators

Indicators serve a crucial role in agri-environmental policy by simplifying, quantifying, and conveying information related to environmental conditions, as well as the various socio-economic aspects of farming, such as inputs, outputs, yields, and economic performance (Bélanger et al., 2012). Their primary significance lies in their ability to facilitate the development of methodologies and models that help us comprehend, evaluate, and manage intricate systems, including agricultural systems and their ecological impacts (Girardin et al., 1999). To illustrate, various environmental indicator frameworks, including DPSIR (Driver-Pressure-State-Impact-Response), LCA (Life Cycle Assessment), and ESI (Environmental Sustainability Index), are employed to gauge and address sustainability concerns (Bell, 2012; Sun et al., 2016; Mangi et al., 2007; Silvestri et al., 2022; Bui et al., 2019). Numerous sets of indicators tailored for different spatial scales are formulated based on these frameworks. For instance, the European Environmental Agency has established a suite of indicators grounded in the DPSIR framework to bolster environmental policy formulation at the EU level (EEA, 2011). In contrast, some indicator sets and tools are specifically designed to assess the environmental performance of individual farms and the products they generate (De Olde et al., 2016ab).

Using a comprehensive set of agri-environmental indicators and productivity metrices, farmers and policymakers can evaluate the impact of their operational and strategic management and policies, linking action focused research to scientific underpinned pathways to sustainability. The implementation and realization of an integrated set of indicators in farm practice as well as policies is challenged by:

- **Fragmented Policies**: Sustainability measures in agriculture often originate from separate policy areas. As a result, there is a lack of comprehensive understanding of how these measures impact each other and their collective feasibility.
- **Lack of Concrete Goals**: Goals related to sustainability are often not clearly defined, making it difficult to determine the necessary efforts to achieve them. Many initiatives focus on improving existing practices, such as efficiency, without specifying the actions needed to attain broader goals, like those related to biodiversity and habitat.
- **Inconsistent Measurement Methods**: Existing instruments and tools do not align to form a holistic view at the landscape or ecosystem level due to inconsistent measurement methods, particularly across different sectors.

- **Context-Dependent Measures**: The effectiveness of sustainability measures depends on the specific context of each farm, including factors like soil type, region, crop rotation, and livestock management.
- **Economic Realities**: Economic constraints often hinder the adoption of costly sustainability measures unless there is a direct financial incentive or reward.
- **Complex Regulatory Environment**: The convergence of various regulations on farms can lead to confusion, inefficiency, and even contradictory implementation of measures. Farmers may find it challenging to navigate and comply with complex and sometimes conflicting rules.

Frameworks for integrated goal-oriented assessment of both the environmental performance of agricultural measures as well as crop yields are essential for sustainable agricultural production as well as unravelling the aforementioned trade-offs and synergies. A wide range of decision support tools (DSTs) using effect indicators have been developed and used over the last decades, providing decision options for policymakers and farmers (Power, 2007). Some of them are strongly focused on a certain topic, such as soil protection (Oleson et al., 2016; Sarangi et al., 2004), precision agriculture (Venkatalakshmi & Devi, 2013), fertigation management (Elia & Conversa, 2015) or specific nutrient measures (Hewett et al., 2004). Others have been developed for a specific geographic context (Manos, et al., 2007) or for land evaluation and spatial planning of sustainable management operations (De la Rosa et al., 2004). Most of these DSTs make use of some form of multi-criteria analysis, focusing on resource allocation for farmers in coordination with environmental protection. These DSTs therefore rely on a series of input databases as a function of the geographic context. Several DSTs explicitly aim for increased resilience of agricultural systems to climate-induced environmental changes (Oleson et al., 2016; Wenkel et al., 2013). Up to now the linkage between management measures and site specific targets is usually weak and strongly dependent on mechanistic models that are difficult to apply at larger scales.

1.4 Objective of this study

In response to these challenges, there is a growing need for an integrated set of goals to which all stakeholders, including policymakers, stakeholders along the supply chain, and the agricultural sector, can collectively contribute. To effectively work toward achieving these goals, it is crucial to provide farmers with a clearer path forward by:

- Setting concrete, time-bound goals,
- Adopting an integrated approach to address these goals comprehensively,
- Ensuring that performance is measurable and rewarded, enabling farmers to see the financial value of their contributions.

Building upon an inventory of existing assessment schemes (and indicators used) for agricultural sustainability across Europe, and insights from processed based models, we identify existing gaps in the use of Key Performance Indicators (KPIs) to assess the relationship between agriculture and environment. This will lead to a robust set of NutriKPIs to be used in the Nutribudget project, allowing farmers to adjust their farm management in view of the agronomic and environmental targets. Creating a standardized way to measure farm performance can provide farmers with clearer guidance on how they can contribute to achieving these goals. Subsequently, it also opens the possibility for other stakeholders, such as national and regional authorities, financiers, stakeholders in the supply chain and nature conservation organizations to valorize these improved performances. Finally, it offers users the opportunity to aggregate the performance of individual farms at higher levels of aggregation, such as national, regional, supply chain, and sector levels.

2. Methodology

This report provides an overview of existing indicators used in national and European policies and market initiatives in relation to agronomic and environmental aims. It proposes a framework and a methodology for assessing the agri-environmental performance of European farms. Before we arrive at those deliverables, we will provide an overview of the research and data organization methodologies.

2.1 QuickScan Literature

We executed a literature scan to gather as many papers as possible that quantify the performance of farming systems in relation to nutrient flows. General search terms such as 'KPI', 'indicator' or 'tool' in combination with 'farming' and 'nutrient' were used in Google Search. We also included tools that we already knew of. These are mostly tools that have been developed in Western Europe in the past decade. During the review of the literature, in an iterative way, we added tools that were referred to in the text but did not appear in our Google Search queries. Whilst extensive, the list of tools is not exhaustive and it may be that the reader has knowledge of tools that could complement the list that is the result of this research.

In the search process, we did not discriminate with regards to the type of tool developer. The work from government bodies, university researchers, private corporations, foundations or NGOs alike, were all included. Therefore, the search results are made up of scientific journal publications, reports and webpage articles. In principle, each tool or assessment framework that is included in the results contains at least one effect indicator or KPI that is related to nutrient application, stocks, balances or losses.

We processed each publication/ reference into a spreadsheet matrix. In this matrix, general information about each tool is recorded:

- name of the tool,
- name of the authors,
- the year of appearance,
- reference to the publication PDF or URL,
- (climate) region and farming system for which the tool is developed.

Next to meta-information about the tools, we extracted, when available, information about:

- The indicator(s) captured by the tool (type and theme, see below)
- Suggested or used target and/or threshold values
- Link to specific policy and/or management practices.

2.2 Classifying indicators and Ecosystem Services (themes)

Each tool of framework is composed of various indicators that, in different ways, provide insight into the characteristics and performance of a farming system. We further classified tools in order to gain a clearer picture of the degree of integrality, as well as the objectives of the tool. The first action we undertook to deconstruct the indicators was to categorize them according to an adapted version of the DPSIR approach[1]. The DPSIR approach is often used as a causal framework in environmental systems analysis, to describe interactions between society and environment. The following types of indicators are distinguished:

- **Pressure indicators,** being indicators related to human activities/external factors that influence the agro-ecosystem, such as nutrient inputs and management measures, including crop, soil, nutrient (and manure) management. These pressure indicators affect the associated nutrient flows and properties of the agro-ecosystem.
- **Effect indicators** (including both state (S) and impact (I) indicators), being the agro-ecosystem

[1] In the original DPSIR framework, five categories are distinguished: driver, pressure, state, impact and response.

properties that change due to the impact of altering nutrient inputs/management measures, such as nutrient uptake such as nutrient uptake, surpluses, losses and pools .

- **Performance indicators**, being properties that reflect the performance of the agro-ecosystem for the associated nutrient uptake, surpluses, losses and pools in view of the agronomic and environmental goals that need to be achieved.
- **Agro-ecological site properties** including the physical-chemical-biological properties of agro-ecosystems that affect the fate of nutrients in the whole farming system.

After having classified the type of indicator, we determined for each indicator the larger theme(s) under which that indicator can be grouped. The list of themes that we used is based on Ecosystem Services (ESS) as listed in the CICES. ESS are defined as "the benefits provided by ecosystems to humans". We distinguish five themes that we consider important when it comes to the role that nutrient stocks and flows play in relation to the environmental performance of agricultural production systems. We acknowledge that themes such as air quality and water quantity (related to crop water requirements, irrigation, etc.) are also important with regard to environmental impacts. However, these play a lesser role in relation to nutrients, therefore we did not consider them as a theme in itself but to be part of a broader theme covering many different aspects..

The classification of themes follows below, with the indented lists showing examples of indicators or sub-themes that are grouped under each theme:

1. **Crop production**: the capacity of a soil/farming system to produce plant biomass for human use, providing food, feed, fiber and fuel within natural or managed ecosystem boundaries.
2. **Climate** (regulation and C sequestration): the capacity of a soil/farming system to reduce the negative impact of increased greenhouse gas (i.e., CO_2, CH_4, and N_2O) emissions on climate
3. **Water quality** (purification and regulation): the capacity of a soil/farming system to prevent from entering and to remove harmful compounds from the water that it holds and to receive, store and conduct water for subsequent use and the prevention of both prolonged droughts and flooding and erosion.
4. **Biodiversity and habitat:** The multitude of (soil) organisms and processes, interacting in an ecosystem, making up a significant part of the soil's natural capital, providing society with a wide range of cultural services and unknown services
5. **Others**: Indicators related to air quality, animal welfare, social-economic characteristics of farmers, and energy consumption.

Each indicator is typically associated with one or more themes. In these cases, we account of the same indicator in each of the themes it can be associated with. Some tools contain indicators that cannot be directly linked to a theme, and are therefore assigned to 'Other' (for e.g. the indicator 'average field size'). All parameters related to soil fertility fall under the theme 'crop production', because we reason that (agronomic) soil fertility is a function of crop production.

Threshold values

An important aspect of KPIs is that they provide a target to which performance can be related and therefore a distance to the target for the system to reach a good performance. This means that threshold values are of key importance, as they determine the boundaries between which the performance of an individual or several aggregated indicators is good, mediocre, or poor. For that reason, in the analysis matrix we have included a variable that shows, in the documents we reviewed, the indicator is accompanied by threshold values.

2.3 Data presentation

In the preceding paragraphs we have discussed the deployed methods for indicator classification. Per tool (or framework), we have summarized the main features. This includes a summation of the themes which pertain to each separate indicator, and a count of the types of indicators (effect, pressure, property or performance). The table also indicates if target and/or threshold values are used. A short written summary follows after each table which describes the context, goals and applicability of each tool.

3. QuickScan KPI-tools

In this chapter we present the results from the executed literature search. We start with a short overview and description of the tools and frameworks that were found. For each tool we summarized the total number of indicators, the number of indicators that are related to each theme and the number of indicators per indicator type, in a table. In the next chapter we present an analysis of the relationship between tools, indicators, indicator types and ESS to get a better understanding of how KPI's are currently used and what kind of knowledge gaps are still present.

3.1 Overview of KPI-tools

A total number of 33 tools have been analysed and processed. The vast majority of tools (22) are developed by researchers and/or government agencies. As government agencies often rely on researchers for in-depth knowledge, there are several cases where there is a collaboration between scientists and governmental agencies. The majority of the documentation of these tools has appeared in the form of scientific journal publications. Only the Agrarumweltmonitoring (AUI) tool was solely developed by a government. The remaining ten tools were developed by consultancies, private companies or are the result of collaboration between private parties (e.g. AgBalance). It is important to note that only a minority of the tools are actually developed in cooperation with farmers or farmer associations. In addition, only a minor part of these tools can be used directly by the farmer or parties in his/her supply chain (i.e. those who support farmers regarding management issues).

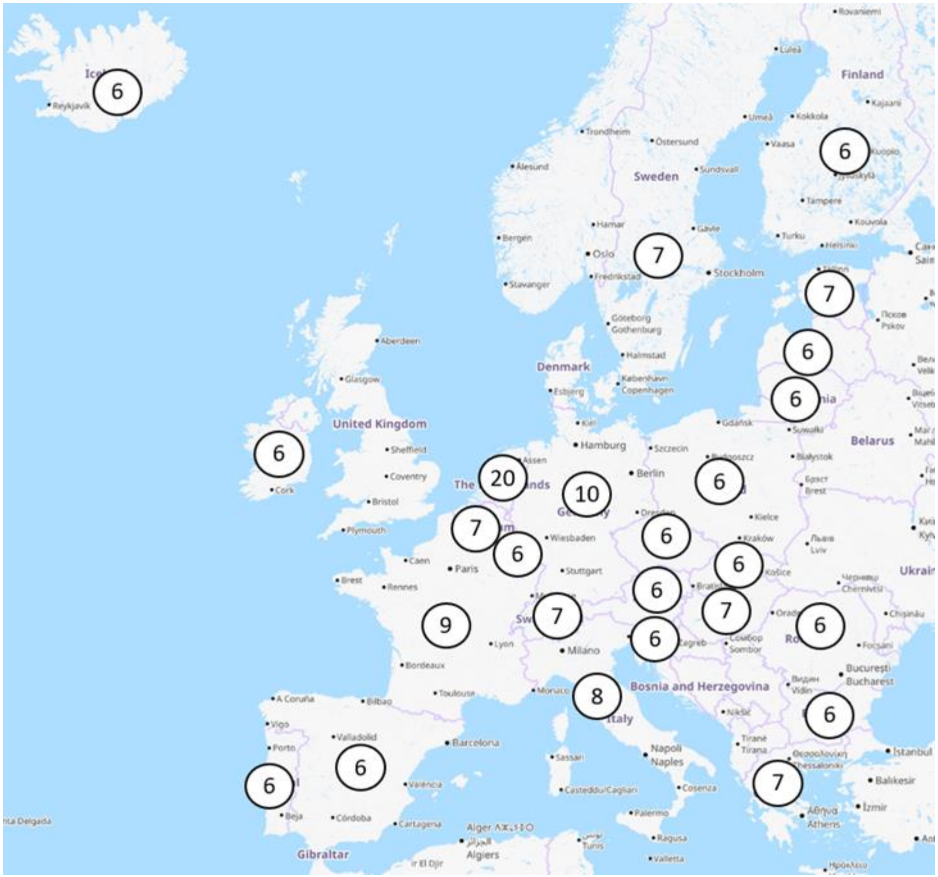

Figure 3.1. Number of tools per European country. The map was retrieved from OpenStreetMap. Please note that We only reviewed some of the existing tools. More tools may exist per country.

The map in Figure 3.1 shows the number of tools that are available per European country. Countries with 6 or 7 tools don't have specific tools developed for their country. Countries like Germany, France, Italy, and especially the Netherlands have more tools that are specifically designed for that country, and these are also countries that deal with large nutrient surpluses in agriculture.

The 33 tools and KPI frameworks aim to support different type of users. In the table below the tools and frameworks are divided over the different user groups for which the tools have been developed.

Type of user	Number of tools
farmer	11
farmer, other actors of supply chain	2
farmer, other actors of supply chain, government	5
government	4
not specified	4
supply chain	7

3.2 Summary of tools[2]

In this chapter all evaluated tools and KPI frameworks were assessed in view of the applicability (scale), the number and type of indicators present (and the presence of target and/or threshold values: scientific based, policy based or expert judgement based), and the connection with one of the five themes (Crop production and soil fertility; Climate (regulation and C sequestration); Water quality (purification and regulation); Biodiversity and habitats, and Others)). Note that and extensive inventory for all tools is available in a separate online database. The references to the sources of each tool can be found in Annex 1.

AESIS

AESIS			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Farm		
Type of user	Farmer, supply chain, government		
Number of indicators	24		
Theme	Count	Type of indicator	Count
Crop production	9	Effect	16
Climate	0	Pressure	4
Biodiversity and habitat	8	Performance	0
Water quality	8	Property	4
Other	7		

AESIS is an indicator-based framework to evaluate sustainability of farming systems. The framework supports decision making at different levels in the agricultural sector and is designed as a holistic information system. AESIS focuses on the environmental and production dimensions of sustainability. The results can be presented in different ways depending on the requirements of the users or the type of evaluation.

[2] Please note that one indicator can fall into and be counted within several themes.

AgBalance®

AgBalance®			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Not specified		
Number of indicators	13 + 2 related to ozone formation		
Theme	Count	Type of indicator	Count
Crop production	3	Effect	10
Climate	1	Pressure	2
Biodiversity and habitat	4	Performance	0
Water quality	3	Property	1
Other	4		

AgBalance® is a tool developed by BASF that provides single and aggregated environmental impact assessments. The single environmental impact covers 15 indicators plus a biodiversity assessment. Two indicators are related to ozone formation, and since that is outside the scope of this analysis, they were not taken into further regard. Aggregated environmental impact summarizes these impact categories in a single result, in accordance with the recommended PEF12 normalization and weighting scheme. The tool can capture the trade-offs across different kinds of environmental impact as well as that between economy and environment implied by certain practices. It has a focus on ecotoxicity, nutrient leaching, air pollution and GHG emissions.

Agrarumweltindikatoren (AUI)

Agrarumweltindikatoren (AUI)			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Farm		
Type of user	Government		
Number of indicators	12		
Theme	Count	Type of indicator	Count
Crop production	7	Effect	9
Climate	2	Pressure	2
Biodiversity and habitat	2	Performance	1
Water quality	5	Property	0
Other	3		

The AUI is part of an agro-environmental monitoring in Switzerland. It evaluates the environmental impact of agriculture. In various areas (nitrogen and phosphorus cycles, energy, climate, soil, water, biodiversity), information is collected to observe and measure the influence of agriculture on environmental quality and the environment's response to agricultural practices. The data is primarily utilized for research, advice, and policymaking. Currently, the datasets from around 300 companies are being evaluated.

ANCA

ANCA			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Supply chain		
Number of indicators	8		
Theme	Count	Type of indicator	Count
Crop production	5	Effect	5
Climate	1	Pressure	2
Biodiversity and habitat	0	Performance	1
Water quality	6	Property	0
Other	3		

The ANCA model is developed to get insight into the fluxes of N and P in Dutch dairy farming. The model calculates the nutrient flows and losses through feed, livestock, manure, soil and crops. The calculated values can be compared to norms in legislation and give an overview of the nutrient flow and nutrient use efficiency at different levels of the farm. The calculation rules in ANCA are updated every year. The most recent version is from December 2022 (Van Dijk et al., 2022).

APOIA-NovoRural

APOIA-NovoRural			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Field, Farm		
Type of user	Farmer		
Number of indicators	20		
Theme	Count	Type of indicator	Count
Crop production	12	Effect	2
Climate	1	Pressure	1
Biodiversity and habitat	6	Performance	0
Water quality	8	Property	17
Other	6		

APOIA-NovoRural is a method for integrated farm sustainability assessment that uses quantitative environmental standards and defined socio-economic benchmarks. Indicators and composite indices are constructed as multi-attribute utility scaling checklists formulated for rural activity assessment considering five sustainability dimensions: i) Landscape ecology, ii) Environmental quality, iii) Sociocultural values, iv) Economic values, and v) Management and administration. With these dimensions it is possible to evaluate the environmental impact of farming systems and alternative practices. The framework consists of 62 indicators divided about the five described dimensions, the results for all indicators are normalized to enable comparison. For this study we only selected the indicators for landscape ecology and soil quality.

Biodiversity Monitor Arable Farming

<table>
<tr><th colspan="4">Biodiversity Monitor Arable Farming</th></tr>
<tr><td>Target and/or threshold values</td><td colspan="3">None</td></tr>
<tr><td>Scale</td><td colspan="3">Farm</td></tr>
<tr><td>Type of user</td><td colspan="3">Supply chain</td></tr>
<tr><td>Number of indicators</td><td colspan="3">8</td></tr>
<tr><th>Theme</th><th>Count</th><th>Type of indicator</th><th>Count</th></tr>
<tr><td>Crop production</td><td>4</td><td>Effect</td><td>5</td></tr>
<tr><td>Climate</td><td>4</td><td>Pressure</td><td>3</td></tr>
<tr><td>Biodiversity and habitat</td><td>2</td><td>Performance</td><td>0</td></tr>
<tr><td>Water quality</td><td>3</td><td>Property</td><td>0</td></tr>
<tr><td>Other</td><td>1</td><td></td><td></td></tr>
</table>

The Biodiversity Monitor Arable Farming (Biodiversiteitsmonitor Akkerbouw) was developed for measuring and monitoring biodiversity restoration in arable farming in the Netherlands. This Biodiversity Monitor uses a set of eight indicators related to land use, fertilisation and management. The relationship with soil quality is still underexposed in this tool. The tool focuses on reaching certain goals, and farmers are free to determine which measures they take to reach these goals. Moreover, it becomes possible for banks, governments and buyers to financially reward farmers for their performance. Threshold values for the indicators still have to be developed.

Biodiversity Monitor Dairy Farming

<table>
<tr><th colspan="4">Biodiversity Monitor Dairy Farming</th></tr>
<tr><td>Target and/or threshold values</td><td colspan="3">All, expert judgement, not documented</td></tr>
<tr><td>Scale</td><td colspan="3">Farm</td></tr>
<tr><td>Type of user</td><td colspan="3">Supply chain</td></tr>
<tr><td>Number of indicators</td><td colspan="3">7</td></tr>
<tr><th>Theme</th><th>Count</th><th>Type of indicator</th><th>Count</th></tr>
<tr><td>Crop production</td><td>2</td><td>Effect</td><td>4</td></tr>
<tr><td>Climate</td><td>3</td><td>Pressure</td><td>3</td></tr>
<tr><td>Biodiversity and habitat</td><td>2</td><td>Performance</td><td>0</td></tr>
<tr><td>Water quality</td><td>1</td><td>Property</td><td>0</td></tr>
<tr><td>Other</td><td>3</td><td></td><td></td></tr>
</table>

The Biodiversity Monitor Dairy Farming (Biodiversiteitsmonitor Melkveehouderij) was developed for measuring and monitoring biodiversity restoration in dairy farming in the Netherlands. This Biodiversity Monitor uses a set of seven indicators related to land use, fertilisation and management. The relationship with soil quality is still underexposed in this tool. The tool focuses on reaching certain goals, farmers are free to determine which measures they take to reach these goals. Moreover, it becomes possible for banks, governments and buyers to financially reward farmers for their performance.

Breitschluh report, 2009

Breitschluh, 2009			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Field, Farm		
Type of user	Farmer, supply chain, government		
Number of indicators	9		
Theme	Count	Type of indicator	Count
Crop production	6	Effect	5
Climate	0	Pressure	1
Biodiversity and habitat	2	Performance	0
Water quality	3	Property	3
Other	1		

The authors have developed a simulation tool to quantify the farm-level environmental impacts that follow from various scenarios of bio-energy production in Germany. Next to the biophysical aspects, social and economic effects are also quantified. The tool allows for assessment of operational production processes at the farm level as well as the creation and evaluation of governmental support programs for agriculture (not discussed in the article itself).

Calker article, 2006

Calker et al., 2006			
Target and/or threshold values	None		
Scale	Field, Farm		
Type of user	Not specified		
Number of indicators	7		
Theme	Count	Type of indicator	Count
Crop production	1	Effect	7
Climate	1	Pressure	0
Biodiversity and habitat	2	Performance	0
Water quality	3	Property	0
Other	0		

In this paper, the authors propose a multi-attribute sustainability function for Dutch dairy farming systems. The function, based on a goal programming approach, enables the calculation of the overall sustainability of a Dutch dairy farm. The sustainability function allows stakeholder groups to assign different weights to the sustainability-related attributes, which encompass the economic, social and biophysical domains.

Cool Farm Tool

Cool Farm Tool			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Farmer, supply chain		
Number of indicators	27		
Theme	Count	Type of indicator	Count
Crop production	1	Effect	25
Climate	27	Pressure	1
Biodiversity and habitat	0	Performance	0
Water quality	0	Property	1
Other	1		

Cool Farm Tool is a globally used carbon accounting tool that allows farmers and farm advisors to steer on carbon flows on the farm level. Each indicator is related to GHG emissions and is quantified in terms of kg CO_2-eq., which is compiled of the CH_4, CO_2 and N_2O emissions related to that particular indicator. Management decisions with regard to crop residue management, tillage, agrochemical inputs use, transportation and storage are parameters that farmers can act upon in order to lower their GHG emissions.

Dantsis article, 2009

Dantsis et al., 2009			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Farm		
Type of user	Not specified		
Number of indicators	4		
Theme	Count	Type of indicator	Count
Crop production	2	Effect	0
Climate	2	Pressure	4
Biodiversity and habitat	2	Performance	0
Water quality	3	Property	0
Other	1		

In this paper, a methodological approach is presented to assess and compare sustainability in agricultural plant production systems at the regional level. Twenty one indicators were selected to asses environmental, economic and social effects of farming systems. Multi-attribute Value Theory was used to come to an integrated assessment of sustainability of the system. Each indicator is scored between 0 and 1 and is ranked and weighted for the calculation of the overall score.

DIALECTE

DIALECTE			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Field, Farm		
Type of user	Farmer		
Number of indicators	14		
Theme	Count	Type of indicator	Count
Crop production	10	Effect	5
Climate	6	Pressure	7
Biodiversity and habitat	3	Performance	2
Water quality	4	Property	0
Other	3		

DIALECTE is an overall assessment tool that evaluates the effects of farming practices and agricultural farming systems on the environment. DIALECTE indicators contribute to the quantitative assessment of the environmental impacts at the farm level. The environmental performance is based on an analysis of mixed character of farm and farming practices (nitrogen management, use of pesticides, irrigation etc.). The tool can be used for an overall approach to evaluate the capacity of the production system to limit the risk of damage to the environment. In the thematic approach, it evaluates the potential impact of the farm system on four environmental components: soil, water, biodiversity and consumption of non-renewable natural resources. The tool returns scores for the indicators, environmental components and weighted farm total.

DLG-Sustainability-Index

DLG-Sustainability-Index			
Target and/or threshold values	Some, policy and expert judgement, documented		
Scale	Farm		
Type of user	Farmer		
Number of indicators	4		
Theme	Count	Type of indicator	Count
Crop production	1	Effect	4
Climate	1	Pressure	0
Biodiversity and habitat	0	Performance	0
Water quality	1	Property	0
Other	0		

The aggregated sustainability index for German agriculture (DLG-Nachhaltigkeits-Index) was developed based on the calculation of the global hunger index. It includes the three sustainability components of economy, ecology and social affairs, weighted equally on the basis of four individual indicators (N surplus, GHG emissions, additional value as result of labor productivity and income comparison). The individual indicators selected for the calculation describe the respective component as representatively as possible by showing a close correlation with other indicators in the respective area. They are easily transferrable to other countries for comparison purposes. For each year an index value is calculated per indicator which is used to evaluate the trend in sustainability over time.

European Analytical Framework for Local Agri-Environmental Programmes

European Analytical Framework for the Development of Local Agri-Environmental Programmes			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Field, Farm		
Type of user	Not specified		
Number of indicators	7		
Theme	Count	Type of indicator	Count
Crop production	3	Effect	5
Climate	2	Pressure	1
Biodiversity and habitat	5	Performance	0
Water quality	0	Property	1
Other	1		

Within the AEMBAC project (“Definition of a common European analytical framework for the development of local agri-environmental programs for biodiversity and landscape conservation”), a set of Environmental Minimum Requirements was developed for seven European countries (Estonia, Germany, Hungary, Italy, Sweden, The Netherlands and Switzerland). This set can be used in the development and evaluation of agri-environmental measures to improve the present situation of agricultural landscapes both from ecological and socio-economic points of view.

FAO – SAFA

FAO – SAFA			
Target and/or threshold values	All, expert judgement, documented		
Scale	Field, Farm		
Type of user	Farmer, supply chain, government		
Number of indicators	12		
Theme	Count	Type of indicator	Count
Crop production	5	Effect	4
Climate	1	Pressure	0
Biodiversity and habitat	5	Performance	0
Water quality	2	Property	8
Other	21		

SAFA (Sustainability Assessment of Food and Agricultural Systems) is a set of guidelines to assess social, economic and environmental sustainability along 21 themes and 58 sub-themes. The goals are universal and can be applied to any farming system. The value ascribed to an indicator is often qualitative, ranging from ‘top level of sustainability performance’ to ‘unacceptable levels of sustainability performance’. Contextualization is necessary to give meaning to the classification of the indicator.

Farm Soil-Water Plan

Farm Soil-Water Plan			
Target and/or threshold values	All, combi of scientific and policy based, documented		
Scale	Field and Farm		
Type of user	Farmer (and advisor)		
Number of indicators	4		
Theme	Count	Type of indicator	Count
Crop production	1	Effect	0
Climate	0	Pressure	0
Biodiversity and habitat	0	Performance	4
Water quality	4	Property	0
Other	0		

The Farm Soil-Water Plan (in Dutch: BedrijfsBodemWaterPlan, BBWP) enables customization per field and farm to contribute to regional goals for clean groundwater and surface water, sufficient water retention and buffering capacity and high nutrient use. It thus facilitates the conversation between farmer and consultant and the realization of the goals of the national Deltaplan for Agricultural Water Management in the Netherlands. The BBWP has been developed by universities, research institutions, soil experts and farmers.

Field to Market Continuous Improvement Accelerator

Field to Market Continuous Improvement Accelerator			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Supply chain		
Number of indicators	7		
Theme	Count	Type of indicator	Count
Crop production	2	Effect	4
Climate	3	Pressure	2
Biodiversity and habitat	1	Performance	0
Water quality	1	Property	1
Other	2		

Field to market is a collaborative effort between farmers, agribusiness, brand and retail companies, environmental organisations and university and government partners to focus specifically on improving environmental outcomes from commodity crop production. The Continuous Improvement Accelerator was developed to enable the private sector to partner around common goals, engage with technical experts and farmers, and design projects to support farmers adopting practices to improve key environmental outcomes. Trends in eight key environmental indicators (land use, soil erosion, irrigation, water use, energy use, GHG emission, biodiversity, soil carbon and water quality) are scored and evaluated over time.

INDIGO

INDIGO			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Farm		
Type of user	Farmer		
Number of indicators	6		
Theme	Count	Type of indicator	Count
Crop production	5	Effect	1
Climate	1	Pressure	5
Biodiversity and habitat	0	Performance	0
Water quality	3	Property	0
Other	1		

INDIGO is an assessment method for sustainability in French viticulture. It is an adapted and elaborated version of the INDIGO method for arable farms. The method uses 6 easily obtainable indicators and scores them on a scale of 0 to 10, each indicator has a defined reference value.

Integral Navigation Toward Goals for Sustainable Agriculture Through Use of KPIs

Integral Navigation Toward Goals for Sustainable Agriculture Through Use of KPIs			
Target and/or threshold values	Under development		
Scale	Farm		
Type of user	Government		
Number of indicators	9		
Theme	Count	Type of indicator	Count
Crop production	4	Effect	5
Climate	3	Pressure	4
Biodiversity and habitat	3	Performance	0
Water quality	3	Property	0
Other	2		

The KPI system Sustainable Circular Agriculture was developed to make it easier for farmers and policymakers to focus on and contribute to goals for sustainable and circular farming. Its framework focuses on integral target management and proposes a set of indicators that can be used to reach the set goals. By implementing and targeting these indicators, effects should be measurable and soil, water and air quality should improve. Also, these indicators make monitoring and rewarding implementation of measures possible. Thresholds for the indicators are not yet developed, but will be in the future.

Label Sustainable Soil Management

Label Sustainable Soil Management			
Target and/or threshold values	All, expert judgement, documented		
Scale	Farm		
Type of user	Farmer, supply chain		
Number of indicators	1		
Theme	Count	Type of indicator	Count
Crop production	1	Effect	0
Climate	0	Pressure	1
Biodiversity and habitat	1	Performance	0
Water quality	0	Property	0
Other	0		

The Label Sustainable Soil Management was developed as a method to value and encourage sustainable soil management in the Netherlands. For each soil type and business type, the conditions (soil management measures) with which a farm complies are assessed. Points are obtained for implementing certain soil management measures. The total number of points determines which label a farm is classified in, ranging from A to D. This should provide an incentive for farmers to manage their soils (more) sustainably. The label has been integrated within the Open Soil Index.

MOTIFS: a monitoring tool for integrated farm sustainability

MOTIFS: a monitoring tool for integrated farm sustainability			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Government		
Number of indicators	21		
Theme	Count	Type of indicator	Count
Crop production	6	Effect	2
Climate	2	Pressure	6
Biodiversity and habitat	5	Performance	4
Water quality	7	Property	9
Other	2		

MOTIFS is an indicator-based monitoring tool for farms. It quantifies social, economic and ecological sustainability aspects. The tool allows for the acknowledgement of weights to the different indicators. Radar charts with performance scales for the various themes are provided as output data. Although quantitative data is used to assign classes and the hereupon based scores to each indicator, the resulting (qualitative) indicator score is portrayed ranging from 0 to 100.

On the Way to Planet Proof – Eggs

On the Way to Planet Proof – Eggs			
Target and/or threshold values	All, expert judgement, documented		
Scale	Farm		
Type of user	Supply chain		
Number of indicators	6		
Theme	Count	Type of indicator	Count
Crop production	0	Effect	5
Climate	2	Pressure	1
Biodiversity and habitat	0	Performance	0
Water quality	0	Property	0
Other	5		

On the way to planet proof is a certificate that ensures consumers that the production of a food product meets certain environmental requirements. The certificate for eggs is developed for poultry farmers with laying hens. Producers may use the quality mark when they comply with a list of criteria. For this analysis we selected 4 criteria that were related to nutrients, energy use and emission of greenhouse gasses. There are also 84 criteria that are related to animal wellbeing, feeding, transport and packaging.

On the Way to Planet Proof – Milk

On the Way to Planet Proof – Milk			
Target and/or threshold values	All, expert judgement, documented		
Scale	Farm		
Type of user	Supply chain		
Number of indicators	7		
Theme	Count	Type of indicator	Count
Crop production	2	Effect	4
Climate	3	Pressure	3
Biodiversity and habitat	2	Performance	0
Water quality	2	Property	0
Other	1		

On the way to planet proof is a certificate that ensures consumers that the production of a food product meets certain environmental requirements. The certificate for milk is developed for dairy farmers producing cow milk. A producers may use the quality mark when they comply with a list of criteria. For this analysis we selected 7 criteria that were related to nutrient and land management and the emission of greenhouse gasses. There are another 32 criteria that are related to animal wellbeing and landscaping.

On the Way to Planet Proof – Plant Production Systems

On the Way to Planet Proof – Plant Production Systems			
Target and/or threshold values	All, expert judgement, documented		
Scale	Farm		
Type of user	Supply chain		
Number of indicators	13		
Theme	**Count**	**Type of indicator**	**Count**
Crop production	8	Effect	5
Climate	8	Pressure	7
Biodiversity and habitat	2	Performance	1
Water quality	4	Property	0
Other	1		

On the way to planet proof is a certificate that ensures consumers that the production of a food product meets certain environmental requirements. The certificate for plant production systems is developed for arable farmers. A producers may use the quality mark when they comply with a list of criteria. For this analysis we selected 13 criteria that were related to nutrient and land management and the emission of greenhouse gasses. There are also 159 criteria that are related to animal wellbeing and landscaping.

Open Soil Index

Open Soil Inex			
Target and/or threshold values	All, scientific, documented		
Scale	Field and Farm		
Type of user	Farmer, supply chain, government		
Number of indicators	25		
Theme	**Count**	**Type of indicator**	**Count**
Crop production	20	Effect	0
Climate	2	Pressure	1
Biodiversity and habitat	1	Performance	25
Water quality	2	Property	0
Other	0		

The Open Soil Index (OSI) is an operational soil evaluation tool in the Netherlands. It provides a comprehensive assessment of soil quality using chemical, physical, biological, environmental and management indicators. At least 21 soil functions are used, with target values set for each function; these are used to determine a distance to target and calculate a score per soil function. The soil function scores are aggregated in the chemical, physical, biological, environmental and management category which in turn are used to calculate a weighted total soil quality score.

Organic Matter Balance

Organic Matter Balance			
Target and/or threshold values	All, expert judgement, documented		
Scale	Field, Farm		
Type of user	Farmer		
Number of indicators	1		
Theme	Count	Type of indicator	Count
Crop production	1	Effect	1
Climate	1	Pressure	0
Biodiversity and habitat	0	Performance	0
Water quality	0	Property	0
Other	0		

The Organic Matter Balance (OMB) is a calculation tool that helps prepare an organic matter balance at plot and farm level. This is done using a calculation with the supply of organic matter (via crop residues and organic fertilizers) and decomposition of soil organic matter. The OMB can be used in obtaining data for the label "On the Way to Planet Proof ". The tools is widely used in agricultural practice, and an integral part of routine soil analyses at farm scale.

Reproduction of Soil Fertility (REPRO)

REPRO			
Target and/or threshold values	All, expert judgement, not documented		
Scale	Farm		
Type of user	Farmer		
Number of indicators	10		
Theme	Count	Type of indicator	Count
Crop production	5	Effect	8
Climate	2	Pressure	2
Biodiversity and habitat	2	Performance	0
Water quality	4	Property	0
Other	3		

REPRO is a tool that evaluates farm sustainability at different spatial and environmental levels. It uses 17 indicators divided over 6 categories (soil, water, air, biodiversity, resources and animal welfare), and some indicators are used in multiple categories. Each indicator has its own threshold values for different levels of sustainability and is scored on a scale of 0 to 1; weighted scores per category are also calculated. These scores can be used to evaluate sustainability and to choose management strategies for improving sustainability.

RISE: Response-Inducing Sustainability Evaluation

RISE: Response-Inducing Sustainability Evaluation			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Government, farmers		
Number of indicators	22		
Theme	Count	Type of indicator	Count
Crop production	12	Effect	3
Climate	5	Pressure	9
Biodiversity and habitat	5	Performance	5
Water quality	4	Property	5
Other	3		

RISE analyses and evaluates the ecological, economic and social sustainability of farms along ten themes and 48 indicators (in the table only biophysical indicators are included). The primary data source are interviews with farmers/farm managers. The model processes the input parameters into a radar chart. It can be used as a diagnostic tool, as well as a monitoring tool. Since 2000 it is actively maintained and deployed to farmers and agricultural extension workers worldwide.

Soil Indicators for Agricultural Soils in The Netherlands

Soil Indicators for Agricultural Soils in The Netherlands			
Target and/or threshold values	All, scientific, documented		
Scale	Field, Farm		
Type of user	Farmer (potentially), supply chain, government		
Number of indicators	40		
Theme	Count	Type of indicator	Count
Crop production	28	Effect	0
Climate	5	Pressure	0
Biodiversity and habitat	4	Performance	40
Water quality	9	Property	0
Other	0		

The purpose of the Soil Indicators for Agricultural Soils in The Netherlands (Bodemindicatoren voor landbouwgronden in Nederland (BLN)) is to make an integrated assessment of the quality of agricultural soils. In the BLN 2.0, the BLN indicator set was integrated with the methodology developed in the OSI and broadened to an assessment of the soil's contribution to several ecosystem services: in primary production, water regulation and self-cleaning capacity, carbon sequestration and climate regulation, soil biodiversity and habitat provision, and nutrient cycling. The BLN calculates scores for indicators related to soil functions based on a distance to target approach. In BLN the indicators scores are aggregated by ecosystem service which are in turn weighted for calculating a soil quality score.

Solagro Carbon Calculator

Solagro Carbon Calculator			
Target and/or threshold values	None		
Scale	Field, Farm		
Type of user	Farmer		
Number of indicators	1		
Theme	Count	Type of indicator	Count
Crop production	0	Effect	1
Climate	1	Pressure	0
Biodiversity and habitat	0	Performance	0
Water quality	0	Property	0
Other	0		

With the Carbon Calculator one can assess the impact of farming on GHG emissions as well as carbon sequestration. The tool also helps to identify relevant sequestration and mitigation measures at farm scale. The tool quantifies emissions from livestock, manure, agricultural inputs, on farm energy use and transport in terms of CO_2, CH_4 and NO_2 emissions. The tool offers 16 possible mitigation and sequestration actions and evaluates the latter based on soil and crop type and effectiveness of sequestration measures.

SyNE

SyNE			
Target and/or threshold values	None		
Scale	Farm		
Type of user	Farmer		
Number of indicators	3		
Theme	Count	Type of indicator	Count
Crop production	0	Effect	1
Climate	0	Pressure	0
Biodiversity and habitat	0	Performance	2
Water quality	0	Property	0
Other	3		

The SyNE calculator is a tool that allows farmers, farm advisors, researchers, and policymakers to calculate three N-related indicators of farming systems: SyNE (system N-efficiency), SyNB (system N-balance) and RNE (relative N-efficiency). The tool also provides insight into other N-related variables (N inputs, N losses during production and transport of inputs, N outputs, and change in soil N).

Total Nitrogen Balance

Total Nitrogen Balance (Balance Globale Azotée)			
Target and/or threshold values	All, expert judgement, documented		
Scale	Field, Farm		
Type of user	Farmer		
Number of indicators	1		
Theme	Count	Type of indicator	Count
Crop production	0	Effect	0
Climate	0	Pressure	0
Biodiversity and habitat	0	Performance	1
Water quality	1	Property	0
Other	0		

The Total Nitrogen Balance (Balance Globale Azotée) is a tool developed to calculate the balance between nitrogen inputs and exports (harvested or grazed crops) at a soil system level. It was initiated in 1988 in France and is regularly updated with new references from ongoing research and evaluation (as a result of changes in the calculation methods)[3].

Viglizzo article, 2005

Viglizzo et al., 2005			
Target and/or threshold values	None		
Scale	Field, Farm		
Type of user	Farmer		
Number of indicators	12		
Theme	Count	Type of indicator	Count
Crop production	4	Effect	4
Climate	2	Pressure	0
Biodiversity and habitat	1	Performance	0
Water quality	5	Property	8
Other	0		

An approach for the assessment of environmental performance of commercial farms in the Pampas of Argentina is provided. The methodological framework to calculate environmental indicators allows farmers to make use of the model themselves. An environmental dashboard graphically portrays the behaviour of individual farms, allowing farmers to steer farm management based on the tool outcomes.

Tools available on global scale

At the global level, several frameworks exist related to the environmental state of farming systems. These include the SEEA EA for Calculating Selected SDG Indicators and the Core food and agricultural indicators for measuring the private sectors' contribution to the SDGs from FAO. While these frameworks claim assessing or reviewing KPIs, the indicators are usually not KPIs: i) landscape elements (e.g. share of woodland of farm) or their change over time, ii) management practices (e.g. % of organic matter input) or iii) ecological functions such as biodiversity. Within the last theme, most indicators focus on soil and water physical and chemical quality, C stocks and GHG emissions. These indicators are often not related to specific targets (environmental or agronomic) or changes in management practices, or are very generic and not linked to any (recommended) area nor farming system. The scale of application is usually not documented.

[3] Francesca Degan has provided a detailed overview of the context in which the TNB/BGA is being used and what the pros and cons of this tool are (Degan et al., 2023).

4. Reflection

The first thing that stood out from the QuickScan of the above-mentioned sources is the difference between tools and frameworks. Certain sources, particularly stand-alone scientific publications, offered frameworks. These frameworks provided suggestions for analysing the performance of farming systems and were in some cases used and applied on a case study. Corresponding results were included in these publications. However, not all these frameworks were developed as a software tool that was actively disseminated amongst farmers (or other targeted users) and maintained (e.g. Calker et al., 2006). For simplicity, in the following section we name frameworks and tools both as 'tools'.

4.1 KPI indicators & themes

Indicators

Of the 33 reviewed tools, 9 tools included indicators related to GHG emissions (Figure 4.1). Although GHG emissions are only partially directly related to nutrient management (N_2O emissions from N fertilizers being the most prominent), in the list of tools it is considered an important part of the performance of farming systems.

The role of soil organic matter, and therefore carbon, is of course important for the immobilization, mineralization and absorption and desorption of macro and micro nutrients. In none of the tools, however, are soil carbon fluxes related to the availability of nutrients.

About 8 tools included an indicator on pesticide use. The negative environmental impact of pesticide use on water quality and biodiversity is considered important. However, to our knowledge, there are no obvious relations between pesticides and nutrient dynamics.

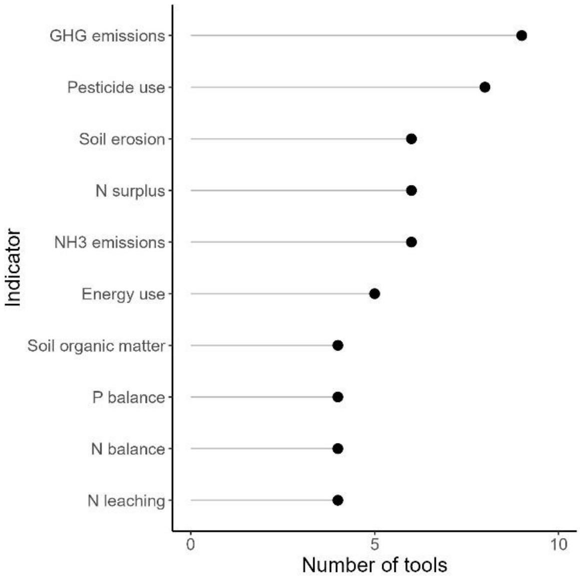

Figure 4.1: Count of indicator appearance in KPI tools.

Evaluating N surpluses and NH_3 emissions come forward in only 6 tools each. This seems rather low, given the importance of N surpluses as a proxy for N losses to the environment. One could argue that N surpluses and N leaching are also an element of a N-balance, which both occurred in 4 tools. When analysing the number of tools where one of the aforementioned N indicators is used, there are in total 14 tools assessing the N inputs or losses. In contrast only 7 tools had indicators relating to the P-balance. The fact that tools use this variety of indicators also shows how diverse the approaches are between tools. In fact, there were 268 unique indicators, of which only 27 occurred in more than one tool.

Assigning indicators to themes showed that all themes were almost equally represented across the tools (Figure 4.2). Crop production, water quality and others were the most recurrent themes, featuring in over 25 tools. Indicators of crop duction were very numerous, despite our choice to leave out certain indicators that were not directly related to crop production, although beneficial for it. For example, the indicator 'soil organic matter content' can be seen as important for crop production due to exchange of cations, the capacity to retain moisture, etc. Indicators of water quality were related to e.g., pesticide use, soil erosion and N surpluses are all related to water quality. Indicators related to the theme 'other' were very diverse; the fact that the majority of tools have indicators related to this theme again shows the diversity in focus of the different tools.

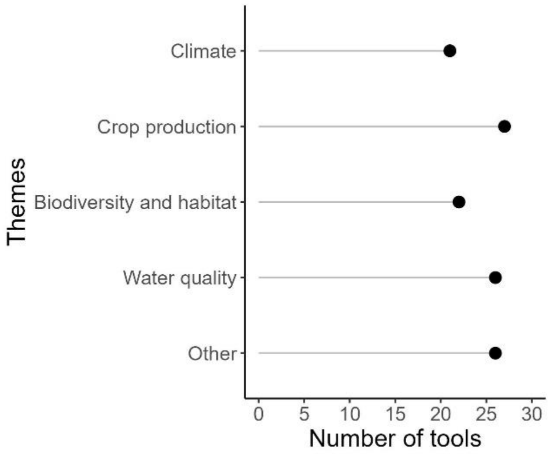

Figure 4.2: The count of tools per theme.

Despite the existence of various tools for agriculture, very few of them evaluate key agronomic measures on a combination of targeted environmental as well as agronomic outcomes in a quantitative way. The reason that many tools are comparatively limited in scope is because they either use very simplified relationships between measures and impacts or they use more process-based models to evaluate the impact of measures. Such a process-based approach is difficult to parameterize (see e.g. Lutz et al., 2019) a for an overview of models assessing losses of N_2O). When applied at a large scale, the only possible way of validation is mostly the use of meta-analysis which can then also be in contrast to model results in view of the complexity of interaction between measures and soil processes results.

4.2 KPI Integrality

An integral approach in the context of Nutribudget implies that a tool covers all the indicators of the farming system that are relevant for optimal nutrient management in relation to the objectives of minimized environmental losses and the maintenance of optimal yields (what 'optimal' means will differ greatly per context).

It is interesting to observe how comprehensive the various tools are, overall. About two thirds of the tools contain a bundle of indicators that cover at least four themes (Figure 4.3). Note that one single indicator can cover multiple themes. For example, the indicator 'length of hedgerows and wood borders', included in the SOLAGRO tool, scores on four themes: soil fertility (i.e. via its impact on erosion prevention, nutrient cycling), climate, biodiversity, and water quantity[4].

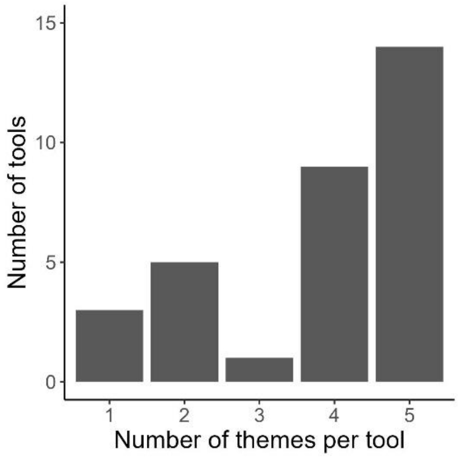

Figure 4.3: The count of tools in relation to the total number of themes per tool

Nevertheless, most tools are highly selective in the measures and indicators included. In addition, since most of the tools highly depend on chemical-physical-biological models or indicators from natural sciences, the end use of tools tends to be oriented to scientists. As a result of both limited focus on economic goals as well as the technical orientation, we find that the sociological aspects of farm management are overlooked. In other words, it is common to find tools and indicators focusing on immediate economic, environmental, and production objectives of farms and watersheds, while tools are missing that are able to capture the more long-term farmer and societal interest in ensuring sustainability of soil resources and environmental objectives. Note that the degree of integrality of each

[4] Hedgerows, when planted along contour lines, can slow down runoff water and retain some of that water through infiltration (Holden et al., 2019).

tool depends largely on the objectives and constraints of the tool designers. Therefore it is not surprising that a fair number of tools have a limited set of (specific) indicators. Examples of such tools are SyNe (N efficiency), Cool Farm (carbon accounting) and the On the Way to Planet Proof Eggs and Dairy (related to specific issues relevant for those sectors).

The main drawback of the integrative tools driven by dynamic or process-based models is that they have a large input data requirement. Finally, tools with a higher level of integration tend not to consider local properties and site characteristics, and vice versa, indicating a trade-off between the number of indicators and management practices covered on the one hand and applicability to various agro-ecosystems on the other. We conclude that there is currently a clear trade-off between the level of modelling support offered versus the data requirement and spatial applicability.

Relationships between themes and indicators

Figure 4.4 shows the total occurrence of various groups of indicators, distributed over the themes they relate to. Of the aggregated indicators, 'other' has the highest count. The high count for theme 'Biodiversity and habitat' is owed largely to indicators related to count of different crop species, presence of natural elements (hedgerows, ponds, woodland, etc.), % of herbaceous grassland, etc.

In second place, 'element balance' has the highest count. This aggregated indicator includes N, P and K balance indicators, C balance indicators (e.g. SOM content) and micronutrient balance indicators. Together they account for the bulk of chemical indicators that say something about soil fertility (pH and CEC fall under the aggregated indicator 'other') and therefore also about crop production. N and P surplus indicators (also aggregated in 'element balance') make up for a large part the count for the theme water quality. Moreover, N leaching or N concentrations in water are also recurring indicators which significantly add to the 'water quality' count.

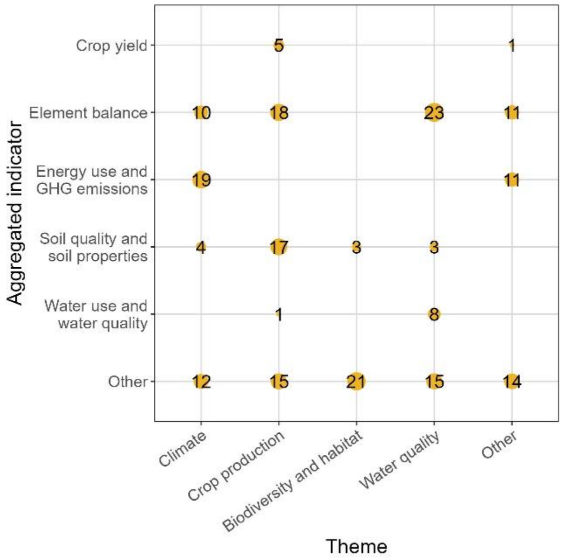

Figure 4.4: Count of intersection between aggregated indicators in relation to theme

Energy use and GHG emissions indicators are quite obviously linked to the 'climate' (which in this case refers to global climate (change), not farm or field level microclimates). The aggregated indicators from this group that are related to the theme 'other' typically contain indicators such as 'share of renewable energy' or 'energy efficiency'. The same evident relationship between an aggregated group of indicators and its theme is applicable to the aggregated indicator 'water use and water quality'. This is exemplified by the often occurring indicators such as 'nitrate concentration in groundwater' and 'nitrogen run-off'.

The high score of aggregated indicator 'soil quality and soil properties' for the theme 'crop production' is much due to the same reason as described in the paragraph above on 'element balance'. Here however, physical and chemical parameters which aren't related to element balances are the major constituents of this aggregated indicator.

Thresholds and trade-offs

About 21 tools have thresholds defined for their indicators. The selection process of threshold values for indicators is not always clear, but in most cases the thresholds are based on regional or generic benchmarks with a presumed relation with crop production, climate, water quality or biodiversity. Quantitative relationships connecting effect indicators to the associated ecosystem services are rare.

Sometimes it is not possible to perform well on each theme. This has to do with trade-offs that are inherent to the framework of each tool as well inherent to the complex reality. For optimal water quality, for example, no application of nutrients would be the best, as N and P leaching would be drastically reduced. Of course, from an agronomic standpoint this is unrealistic: in order to obtain decent or specifically high yields, nutrient surpluses and therefore nutrient losses, are unavoidable.

4.3 Synthesis

The analysis of KPI tools for agro-environmental performance has shown that there is a large variation amongst tools. The primary observation here is that many tools provide indicators but not key performance indicators. The indicators which we identified were often effect indicators. They were not 'key' performance indicators in the sense that:

a) They did not always contain threshold values. This is really important because a performance indicator ipso facto implies the existence of a target or threshold value.
b) A performance indicator is not necessarily a 'key' performance indicator. A KPI is clearly linked to a specific goal and can be compiled of several performance indicators.

Furthermore, indicators are often clearly linked, yet not always explicitly, to ESS or themes, but the balanced representation of different ESS and their relation to performance indicators is not always comprehensive[5]. This is partially caused by the goals of the tools that were included in this analysis. Some indicators are more commonly used in the reviewed tools than others. However, for the development of a European tool that quantifies agro-environmental performance, an integrative and transparent approach is important. This is particularly important with regard to the weighing of (key) performance indicators, where a particular indicator could be more or less important, depending on the geographic and legislative context.

Another aspect which has not been mentioned so far is that KPI frameworks and tools often don't include nor discuss the potential of their indicators for cost and benefit analyses[6], on both the short and the long term. This is essential for farmers who want to implement a management change. Uncertainty associated with changes in the management regime may inhibit farmers from making changes, even though potential benefits could outweigh the drawbacks (both on the short and the long term).

Earlier on, mention was made of the not always clear method of assigning thresholds to indicators. Thresholds are very important for the establishment of the range of a KPI score (the 'lower' the bar, the easier it is to score well, and vice versa). Local circumstances such as soil type and geographical context (e.g. the presence of Nature2000 areas or drinking water wells) are paramount in determining the threshold values. However, the instalment of certain threshold should show a clear (quantitative) science-based link with the relevant ESS. The same goes for management practices with regard to their effect on ESS functioning. This topic is described in more detail in section 5.

[5] Please keep in mind that we did not look at all ESS but only those that are relevant when focusing on nutrients
[6] Within the Nutribudget, we do not tackle the socio-economic aspects of the C and nutrients budgeting.

5. NutriKPI framework for NutriBudget

5.1 KPI selection

Farm-level tools or KPI frameworks for assessing agricultural sustainability provide an alternative approach to conventional land management directives. These tools offer measurements and indicators that empower farmers to devise their sustainability strategies while aligning with the objectives set by policymakers (Schulte-Uebbing et al., 2022; Kleijn et al., 2020). However, it's important to note that some farm-level indicators recommend specific agricultural practices. Payraudeau and van der Werf (2005) categorise these as "means-based indicators" (e.g., nitrogen fertiliser application), distinct from "effect-based" indicators (e.g., nitrate loss to groundwater and surface water). Means-based indicators serve as proxies for desired environmental conditions (Bélanger et al., 2012) and are more practical to measure or estimate at the farm level compared to effect-based indicators (Girardin et al., 1999). In contrast, effect-based indicators encompass emissions, impacts, and the current state of environmental aspects, enabling farmers to determine how they can influence these outcomes. These indicators offer a more comprehensive view of the environmental effects of their practices and guide farmers in making informed decisions to achieve desired sustainability goals.

An integrated indicator-based agricultural assessment system possesses two fundamental items:

- **Comprehensive Coverage of Sustainability Dimensions**: It encompasses the three core pillars of sustainability, which include the environmental, social, and economic aspects. This coverage extends to critical factors like biodiversity, water quality, and climate change. Notably, international organizations like the FAO (Food and Agricultural Organization) emphasize the importance of evaluating agricultural systems holistically, considering the balance between environmental, social, and economic dimensions. This approach also addresses crucial issues such as food security and equitable wages, as emphasized by Bonisoli et al. (2018).
- **Incorporation of Multiple Sustainability Dimensions**: According to Silvestri et al. (2022), employing an integrated set of indicators, encompassing environmental, social, and economic aspects, facilitates a smoother transition toward sustainability. However, despite the call for integrated indicator sets, earlier research comparing a series of indicator-based agricultural assessment systems as well our QuickScan (chapter 3) revealed that the majority concentrated solely on one or two dimensions of sustainability (de Olde et al., 2016a). An effective integrated system guides efforts toward achieving sustainability goals across environmental, social, and economic realms, while also addressing distinct dimensions within environmental sustainability.

Hence, an integral assessment system must set targets for each of these environmental issues. The underlying algorithms, linking indicators to the agronomic and environmental targets, should be well justified from experimental data or models. When linking means-based and effect-based indicators, the evaluation of measures should follow scientific sound relationships as well. When more sophisticated statistical models are used to link measures and their impact, then the observed relationships (and analysis of causal patterns and impact analysis) should be clear and the statistical performance of these models should be tested on independent test sets.

Means-based indicators, due to their prescriptive nature, can sometimes suffer from a narrow focus akin to the single-issue approach observed in land management prescriptions. In contrast, effect-based indicators, with their descriptive approach, circumvent this limitation. The changes in farming practices recommended by means-based indicators can yield diverse and uncertain impacts on sustainability objectives. By employing modelling techniques to unravel the causal relationships between means-based and effect-based indicators, these effects become more apparent. This modelling approach empowers indicator developers to manage trade-offs and foster synergies within the indicator set (Nicholson et al., 2019).

For that reason, NutriBudget strongly focuses on the use of carbon and nutrient surpluses as (key) effect indicators for which specific thresholds can be defined in view of the multidimensional agronomic and environmental targets. Modelling also holds pivotal importance in terms of indicator relevance, which refers to the extent to which an indicator enhances the likelihood of achieving the implied goal. By uncovering how means-based indicators influence emission, impact, and state variables, developers can assess whether these indicators accurately represent the environmental conditions they are meant to proxy (Hill et al., 2016; Watermeyer et al., 2020; Nicholson et al., 2019).

Among the KPI tools evaluated, the majority is applicable to all agricultural sectors and a few of them are broadly applicable across Europe. Most of the KPI tools do not account for spatial variability related to soil properties and climate characteristics, among others, neither in the definition of the indicators, nor in the definition of thresholds. In NutriBudget, we aim at defining indicators and thresholds targeted to local conditions. Earlier reviews confirm that there is no one-size-fits-all solution (Schader et al., 2014) and that either the thresholds should depend on local site conditions or that even the selection of KPIs would vary by region (Cândido et al., 2015; de Olde et al., 2016b). In 2011, Acosta-Alba & Van der Werf suggested that the use of normative target values (or thresholds) would be required to avoid pollution swapping and clear monitoring of farm sustainability. Similarly, Ros et al. (2022) and Bampa et al. (2019) defined a scalable framework to assess and evaluate the soil health in view of various ecosystem functioning using agronomic (and generic) approaches to underpin localised threshold values for these functions. In contrast to normative target values, relative target values are often used to benchmark farmers with themselves or their peers, limiting the actual learning curve and Plan-Do-Check-Act cycle farmers have to undergo to increase their productivity while minimising the environmental impact. Normative values ensure that the steering done by these systems results in improvements necessary to maintain ecologically functional landscapes (Kleijn et al., 2020).

In theory it is possible to combine multiple KPI systems across Europe while accounting for various farming systems across diverse landscapes, provided that these systems adopt normative target values for indicators. However, in practice, this endeavour becomes formidable due to the need to operationalize an impractical number of assessment systems, each specialized in appraising specific farm types within distinct landscapes. Additionally, examinations of indicator-based agricultural assessment systems highlight a noteworthy array of variations in score computation, aggregation methods, input requisites, terminology, data sources, target audiences, and presentation formats for results (De Olde et al., 2016b; Acosta-Alba & Van der Werf, 2011). Each of these aspects would necessitate attention and standardisation. This challenge underscores the need for a scalable system that can expand both vertically (across different tiers of assessment) and horizontally (across various agricultural sectors).

As being said, carbon and nutrient balances are of direct relevance to policies relating to agriculture and the environment including climate change, air quality, water quality, and biodiversity. They have been used as a high-level indicator of farming's pressure on the environment and how that pressure is changing over time. Note that these balances do not necessarily estimate the actual losses of nutrients to the environment, but significant nutrient surpluses are directly linked with losses, with the actual losses varying with site conditions. They also allow direct feedback on farm management, giving great opportunities to guide farming systems in their roadmap to a more sustainable carbon and nutrient use in agriculture. Since these balances link to multiple agronomic and environmental performance indicators of farming systems and since they can be implemented for all agricultural systems across Europe we select them to guide the Nutribudget project which aims to "*systematically optimize nutrient flow and budget across different agricultural production systems and regions in the EU to limit and reduce pollution due to the excessive use of nutrients and nutrient losses to the environment*". The additional advantage of these carbon and nutrient balances is that they can be applied on various spatial and temporal scales, allowing generic scalability and facilitating integrative assessments of farms and farming systems in view of the desired targets given by the NutriBudget project, including water quality (mainly nitrogen and phosphorus), air quality (mainly carbon and nitrogen), biodiversity (mainly ammonia), climate (mainly carbon) and soil quality (mainly carbon, cations and anions). The supportive finding that most of the current KPI-tools being in use in Europe also include the concept of nutrient balances confirms that the selection of these KPIs is relevant and useful to guide the overall aims of the Nutribudget project.

The carbon and nutrient surpluses (sometimes referred to as nutrient budgets or nutrient balances) can be estimated on farm (also called farm balance) and field level (often called soil nutrient balance). The nutrient surplus in agriculture (both on field, farm and regional level) is equivalent to inputs of nutrients minus outputs of nutrients as contained in animal and plant products as well as in manure removed from agriculture. A surplus means that there is loss of nutrients into soil as well as into air in the case of nitrogen. A farm surplus for nutrients relates to the overall nutrient balance at the farm level, considering inputs and outputs as well the impact of manure treatment technologies and housing systems, while a soil surplus for nutrients focuses specifically on the excess nutrients present in the soil compared to what is required for plant growth. Both concepts however refer to the same mass balance principle and are therefore important for sustainable agriculture and environmental protection, as they help in managing nutrient use efficiency and minimizing the environmental impact of nutrient runoff.

Additional to the carbon and nutrient balances we selected two potential extra indicators, that are partly beyond the focus of the NutriBudget project, in relation to crop biodiversification (in time and space) and pesticide use, being relevant for aboveground biodiversity and water quality. These two indicators can easily be accessed from farm data or derived from satellite derived indices, thus being measurement based. We propose to use these two KPIs as optional ones, thereby strengthening the environmental impact of the proposed measures in the NutriBudget project.

The calculation of the nitrogen surplus can be done as follows:

$$N_{sur} = N_{in} - N_{out} - N_{em} + N_{mi} \quad (1)$$

where:

N_{sur} = N surplus available for subsurface runoff, leaching and denitrification (kg N ha^{-1} yr^{-1})

N_{in} = Total N input via fertiliser, manure application, grazing, biosolids, atmospheric deposition, and biological N fixation (kg N ha^{-1} yr^{-1})

N_{out} = Crop N uptake via harvested crops and crop residues removed (kg N ha^{-1} yr^{-1})

N_{em} = Total N gaseous (NH_3, N_2O, NO_x) emission from soil applied fertiliser, manure, grazing, atmospheric deposition and biological N fixation (kg N ha^{-1} yr^{-1})

N_{mi} = Net N mineralisation (kg N ha^{-1} yr^{-1})

Note that for the farm nitrogen surplus the internal N fluxes from mineralisation is set to zero, and then the inputs includes the inputs from manure (when imported from other farms), fertilizers, fixation and deposition and the inputs via feed, and the outputs are the products leaving the farm by crops (arable farms), milk, eggs and meat (husbandry farming). The subtraction of gaseous emissions is optional, and can also be considered as a loss to be estimated from the N surplus.

For all other elements (carbon, phosphorus, potassium, magnesium, calcium, zinc and copper) the soil surplus can be calculated as follows:

$$X_{sur} = X_{in} - X_{out} + X_{soilsupply} \quad (2)$$

where X represents the specific elements (all in units kg ha^{-1} yr^{-1}), the inputs of these elements originate from added fertilizers, manure, biosolids, deposition of manure during grazing, and atmospheric deposition. For the farm budget, the soil supply is again considered as an internal flux that is not used in the calculation of farm balances whereas X_{out} represents the nutrient output leaving the farm.

The selected KPIs and their interests for achieving the NutriBudget targets are summarized below:

KPI surplus for	Water quality	Biodiversity	Climate	Soil Health	Crop yield
Carbon			X	X	X
Nitrogen	X	X	X	X	X
Phosphorus	X			X	X
Cations				X	X
Metals				X	X

Conclusion: There is a strong connection between carbon and nutrient surpluses on the one hand and the agronomic and environmental targets that agriculture has to achieve to be sustainable on the long term on the other. These surpluses also have a strong horizontal and vertical scalability for monitoring and application in fertilizer recommendation tools. Lastly they can be influenced by the field and farm management while accounting for site properties. For these reasons we conclude that the carbon and nutrient budgets can be used as key performance indicators to monitor the farm performance in view of the European aims for a zero-pollution-agriculture.

5.2 Derivation of critical thresholds

A desired nutrient and C state refers to potential target values for soil quality indicators (linked to crop production) and critical values for air and water quality indicators (linked to environmental protection) will be derived from the process-based models in the NutriBudget project. Data on these targets and critical values can be obtained from existing databases or national reports.

Critical targets and threshold values for nitrogen can be derived via the spatially explicit N-balance approach designed by De Vries et al. (2021) for environmental thresholds in relation to i) N deposition onto natural areas to protect terrestrial biodiversity (critical N loads), ii) N concentration in runoff to surface water (2.5 mg N L^{-1}) to protect aquatic ecosystems and (iii) nitrate concentration in leachate to groundwater (50 mg NO_3 L^{-1}) to meet the EU drinking water standard. These critical N inputs to achieve the environmental thresholds and their exceedances can inform more targeted mitigation policies than flat-rate targets for N loss reductions currently mentioned in EU policies.

Sustainable P management, which aims to grow crops without P limitation while avoiding P losses to environment is crucial to: (i) achieve food security (Koning et al., 2008), linked to the Sustainable Development Goal SDG2 (zero hunger) and (ii) avoid threats to achieving SDG14 (life below water) due to P losses from farm fields by enhanced surface P runoff and consequent eutrophication of freshwater and coastal seas. Sustainable P management can be based on the “Build-up or mining and Maintenance” approach. Depending on whether soil P availability (as being assessed by a soil P test) is high, low, or optimal, P fertilizer inputs can be less than, more than, or equal to crop P removal, respectively. Recently de Vries et al. (2024) designed a spatially explicit P-balance approach to assess the current P surplus in view of both crop yield and the losses via leaching and erosion. The same approach is applicable for the other nutrients K, Mg and Ca, where the latter is defined in view of the desired change in base cation pools to counteract acidification below an agronomic threshold while accounting for the site conditions controlling the acidity buffering of the soil).

Soil organic matter is a key parameter for a healthy and high-quality agricultural soil and drives soil processes controlling both crop yield and environmental losses. A critical threshold for SOC below which the soil becomes less fertile and sustainable is however missing. Consideration of such critical levels involves assessment of the quantitative evidence, i.e. the nature of SOM and the properties it confers on soils, whether justifiable limits can be set for a range of soil types, climatic conditions, or land management/cropping practices and, finally, whether there are any trade-offs from an increase in SOC levels in soils. Using quantitative relationships derived from literature Ros et al. (2024) assessed the contribution of SOC to a series of agronomic and environmental relevant soil functions and properties, and linked this contribution to critical targets for the soil functions evaluated. Using this a critical SOC value, as well an optimum range of SOC, can be defined for agricultural soils.

Note that the derivation of critical thresholds and targets will vary over space given the site conditions controlling the agronomic and environmental impacts as well the environmental targets to achieve (e.g. distance to nearby nature areas, the vulnerability for nitrate leaching). This allows a spatial explicit monitoring and assessment of KPIs taken into account the spatial variability in soils, climatic conditions and farming systems.

Conclusion: critical thresholds or targets can be derived for the selected NutriKPIs using the model framework developed within the NutriBudget project. Targets and critical values can be obtained from existing databases or national reports and will be tailored to the farming system and regional contexts.

5.3 Use of means-based vs. effect-based indicators

Means-based KPIs focus on assessing the specific practices and inputs used on a farm, such as fertiliser application rates, pesticide usage, or the adoption of buffer strips and cover crops. The use of means-based KPIs has the advantage that farmers have direct control over the implementation on field and farm level, and these KPIs are usually easier to measure and track for monitoring purposes. Their main disadvantage is their limited score since they not directly reflect environmental outcomes and can lead to a narrow, single-issue approach on the one hand, and they do not account for interactions and complexities of farming systems on the other. Effect-based KPIs assess the actual environmental outcomes or impacts resulting from farm practices, providing a direct assessment of the farm's environmental and agronomic performance, and indirect or direct also on its impact on air, soil water, biodiversity and climate. They offer a holistic approach, considering multiple environmental dimensions simultaneously but often require more complex measurement methods and data collection. Means-based KPIs focus on farm practices and inputs, offering simplicity and direct control, while effect-based KPIs assess actual environmental outcomes, providing a comprehensive view of sustainability. Combining both types of indicators can offer a more balanced and informative approach to farm sustainability assessment, addressing both practices and their environmental consequences.

The combination of both type of indicators can be beneficial for the following reasons:

- Means-based indicators provide insights into the specific practices and inputs used on the farm, while effect-based indicators reveal the actual environmental impacts of those practices. This **comprehensive** assessment considers both the "how" (practices) and the "what" (environmental outcomes) of farming.
- Farms are complex systems where multiple practices interact to produce environmental outcomes. Effect-based indicators provide a **holistic understanding** of how these interactions affect the environment, encompassing air quality, soil quality, water quality, biodiversity, and climate. For example, assessing the effect of different tillage practices (means-based) on soil erosion rates (effect-based) provides a more complete picture of their sustainability implications.
- While effect-based indicators directly measure environmental impacts, means-based indicators offer insights into the management choices that influence those impacts. Combining these types of indicators enables farmers to identify which specific practices contribute to positive or negative outcomes. This information empowers them to make **informed decisions** for sustainable farming.
- Many agricultural policies and regulations focus on both practices and outcomes. Integrating both types of indicators **aligns farm assessments with policy objectives**, ensuring that farmers meet not only specific practice requirements but also achieve desired environmental goals.
- Europe encompasses a wide range of farming systems, from intensive monocultures to diverse agroecological approaches. Different types of indicators may be more relevant for specific systems. A combined approach allows for **flexibility**, tailoring the assessment to the characteristics and goals of each farming system.

Within the NutriKPI framework we strongly focus on the use of carbon and nutrient surpluses as KPIs (being an effect-based indicator) to monitor and assess the farm sustainability performance, whereas the actual and desired surplus is derived from the properties of the farming system including common management practices applied. Based on the farm performance, farmers will receive tailormade solutions (crop, soil, fertiliser or manure treatment measures) to improve the farm performance, thereby connecting the "means" with the actual effect-indicators used to quantify the farm performance. Within the decision support tool it might additionally be beneficial to include a few number of "easy-to-measure" means-based indicators, and user derived inputs for the development of the decision support tool (to be done in WP5 of the NutriBudget project) will guide this decision.

These might include all "simple" measures from the Measurement Catalogue (designed in WP1 of the NutriBudget project with estimated impacts on environmental and agronomic goals via the models of WP2 in the same project). A few of them (like cover cropping, no-tillage, spatial variability in soil fertility) might be derived from open-source satellite data, thereby stimulating farmers to use this knowledge to optimise their crop, soil, water and nutrient management. On the long term the implementation of these measures will help to reconcile agronomic and environmental targets for carbon and nutrient surpluses on field and farm level.

Conclusion: the NutriKPI framework is based on effect-indicators showing the contribution of farms to multiple ecosystem services. Mean-based indicators like the implementation of specific measures for crop, soil, water and fertiliser management or treatment (derived from the Measurement Catalogue) will be used to guide, stimulate and improve the actual farm sustainability performance.

5.4 Assessing integrative farm performance

Once the relevant NutriKPIs for a combination of goals or ecosystem services have been identified, the challenge arises of weighing these various KPIs against each other to create an overall score that comprehensively assesses the sustainability performance of agricultural farms. It may also be necessary to aggregate multiple indicators (e.g. for each nutrient) into groups that provide direction for interpreting farm sustainability. For example, all indicators for each nutrient can be aggregated in view of the ecosystem services crop production, water quality, climate, and biodiversity. After aggregating individual KPIs, these KPIs together can be translated into a scoring or assessment of the overall farming sustainability. In practice, this aggregation is primarily used from a user perspective to grasp the key issues for sustainable farm management, as well as the potential for improvement through crop, soil, and fertiliser practices. Finally, if the goal is to arrive at a single integrated score of farm sustainability, an aggregation of the scores per ecosystem service must be conducted.

A very straightforward aggregation method is the "one out, all out" approach (Bouma et al., 2022). In this method, if any of the KPIs does not meet the target value, the KPI is considered insufficient. Only when all KPIs are satisfactory is the farm sustainability deemed good. This method often leads to the conclusion that farm sustainability is inadequate in most cases unless the target values are set at a very low level. Additionally, this approach overlooks the complexity of farming systems (as well their relation with regional targets affected by landscape properties), where a deficiency in one aspect can be compensated for by interactions with other. A single shortcoming may not necessarily indicate inadequate farm performance for agronomic or environmental targets. It is currently under debate whether the socio-economic position of the farm(er) might act as such a unique KPI overruling all other KPIs. Within the current proposal we focus on the agronomic and environmental performance of farming, without actual quantification of costs and benefits of reaching the desired KPI thresholds.

The most common method for generating a score for aggregated groups of indicators involves the use of averaging, often applied in soil quality assessments, assuming that individual assessments are additive and equivalent (Fine et al., 2017; Svoray et al., 2015). While this approach can be useful for a quick assessment, it disregards the diversity of functions, the interactions between them, and the fact that many underling processes controlling crop yield and environmental losses are non-linear. More recent approaches use a weighted average, still assuming that the various indicators and functions are additive. This assumption builds upon the classical concept of Liebig's Law of the Minimum, where the functioning of an agricultural soil (or even ecosystem) is hindered by its least functional component. The weighting of individual functions and indicators can be based on empirical data, literature, or expert knowledge, depending on the desired goal or ecosystem service (Andrews et al., 2002; Krueger et al., 2012; Wienhold et al., 2004; Pulido Moncada et al., 2014).

The mutual weighting of different indicators and their relevance in achieving a goal is either ignored in the scientific literature (meaning each indicator contributes equally) or is based on expert knowledge or the use of statistical techniques that search for relationships between individual functions and the external target variable within large datasets. The main challenge with the latter approach is the requirement for extensive databases that encompass all components of the farming systems, the environmental and agronomic targets, as well as historical management and practices. The financial costs and benefits are usually not considered at all. Currently, such integrative datasets are either lacking or very limited, leading most tools to rely on expert knowledge.

In any case, the aggregation of individual KPIs into an integrated final score is subjective (Rinot et al., 2019), especially when evaluating the farms contribution to multiple ecosystem services. There is no scientifically correct method that can universally be applied in all cases. The comprehensive assessment of farms across various objectives (crop, water, climate, etc.) requires a relative weighting of the desired objectives for which the soil will be used. This is a political or policy decision and cannot be solely based on scientific knowledge or experiments. While science can provide some guidance, it cannot provide a definitive answer. However, a definition of farm sustainability can be given, as well as a management approach that maximises multiple objectives simultaneously. Through optimised crop, soil and nutrient management, targeted efforts can also be made to find measures that can offset negative effects for a specific function or ecosystem service. In essence, it is currently desirable to give equal weight to each ecosystem service when calculating an integrated soil quality score. However, it should be noted that at the regional level, differentiation among ecosystem services can be made based on "what is possible."

This subjectivity in the calculation of integrated farm performance scores also emphasizes the importance for a NutriModel and NutriPlatform DST to provide insight into the choices made, and for users to gain an understanding of the scores of the underlying KPIs before they are aggregated into scores representing integrated farm performance. Concrete actions and solutions can also be identified at the level of individual KPIs, shaping the practical perspective.

Conclusion: we propose to aggregate all the effect indicators into four so-called NutriKPIs with specific thresholds for soil fertility (in view of targets for crop production), water quality (in view of targets for nutrient concentrations in groundwater and surface water), climate (in view of targets for carbon neutrality) and biodiversity (in view of targets for ammonia emission as well crop biodiversity). The aggregation in a final score is scientifically not possible, and this aggregation is made user dependent.

5.5 Synthesis: principles of the NutriKPI framework

The KPI framework to be applied in the NutriBudget approach is illustrated below. The overall goal of optimising carbon and nutrient flows on field, farm and regional level is to improve the sustainability of agriculture. To reach this target, we disentangle the overall goal in four specific objectives in view of their applicability in such a KPI framework. These specific objectives include the ecosystem services related to crop production, water quality, carbon neutrality and biodiversity. To achieve these objectives, field and farms can be assessed and monitored via specific KPIs for soil fertility (contributing to all goals, but in particular to crop production), water quality, climate and biodiversity. These KPIs, being derived from measured or calculated field and farm properties, provide a solid link to the desired farm management practices. However, it does not imply that separate effect indicators should be created for each specific objective: the carbon and nutrient surpluses (estimated on field or farm level) can be evaluated in view of desired targets for both crop production, good water quality and carbon neutrality. Ultimately, it is about an integrated set of KPIs that collectively serve the objectives. At the bottom of the figure there are the measures that farmers can apply on their farms (linked to the Measurement Catalogue developed in WP1). Objectives and measures converge in the middle: at the level of the KPIs, which together form an integrated set of NutriKPIs linking farm performance to the overall goals of sustainability. The combination of objectives, the KPI set, and potential measures constitutes the NutriKPI framework.

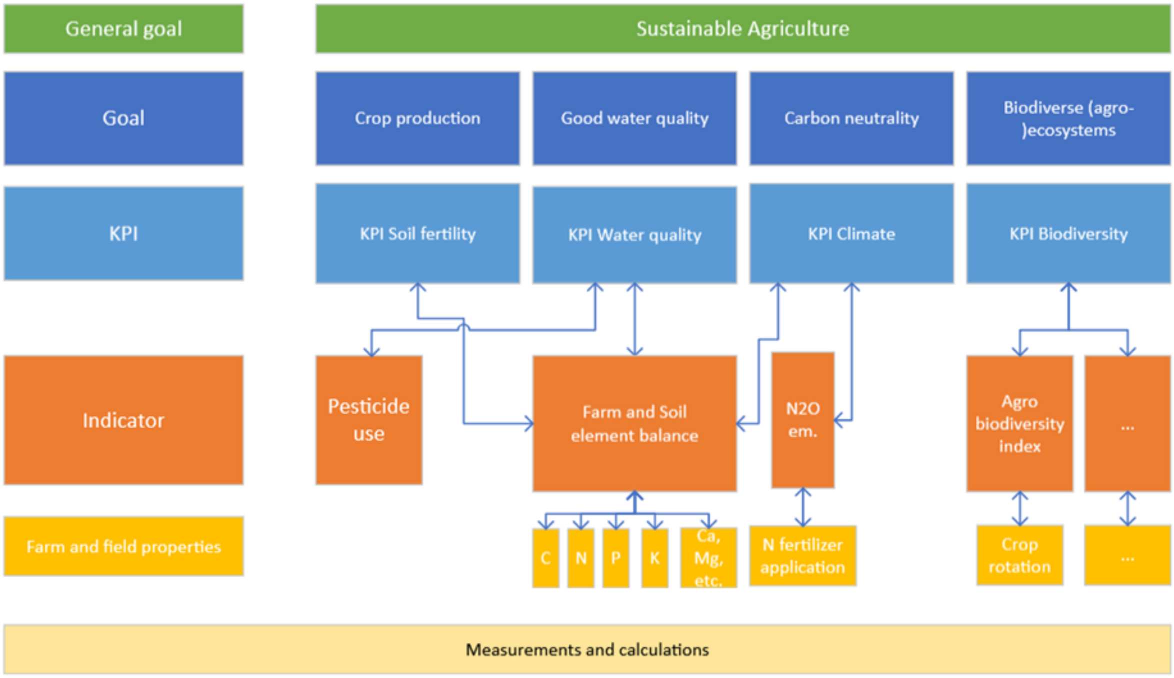

Figure 5.1 Conceptual approach for the NutriKPI framework illustrating the coherence between targets for sustainable agriculture, key performance indicators, field and farm properties and measures to be taken to improve the sustainability.

For the delineation of the intended operation of the system, the following principles are applied:

- the NutriKPI framework is based on the following general objectives: 1) improving the agricultural production (crop and animals) and crop health; 2) improving water quality and management, 3) mitigating climate change, and 4) maintaining and/or restoring biodiversity. We assume that the improvement of agricultural production also enhances the socio-economic position of the farmer, without adding this as a separate objective. Since the proposed NutriKPIs include specific targets for farm and soil surpluses of carbon and nutrients in view of the four objectives, this already includes targets like improving circularity and improving soil health. The derivation of targets and threshold for the NutriKPIs will follow (inter)national commitments.
- The NutriKPI framework portrays the performance of individual entrepreneurs in the agricultural sector at the farm level. It concerns performance aspects that farmers can influence and can be determined per farm but can be aggregated to various spatial scales (field, farm, regional) relevant to the objectives.
- The NutriKPI framework fits to the production environment of agricultural farms and the agro-ecosystem properties affecting (and controlling) its agronomic and environmental impacts. Therefore, the proposed NutriKPIs relates to the specific conditions in its immediate surroundings. However, the transfer of negative effects to other areas should be prevented. In principle, the framework is applicable for all farm types independent of the farming strategy (conventional, agro-ecological, regenerative or organic).
- The NutriKPI framework connects different spatial scale levels by translating performance at the farm level into contributions to objectives at higher scale levels and vice versa: objectives at different scale levels (countries, regions, sectors, supply chains) are translated into performance at the farm level.

Annexes

Annex 1 References to sources of tools

Tabel S1. Overview of tools with their source to find background documentation.

First author	Tool name	URL
van Doorn	Integraal sturen op doelen voor duurzame landbouw via KPI's	https://edepot.wur.nl/548327
van der Wal	Ontwerp Label Duurzaam Bodembeheer	https://www.clm.nl/wp-content/uploads/2021/09/910-CLMrapport-Ontwerp_Label_Duurzaam_Bodembeheer_ASR.pdf
van Laarhoven	Biodiversiteitsmonitor melkveehouderij	https://biodiversiteitsmonitor.nl/docs/Biodiversiteitsmonitor_engels.pdf
Ros	BedrijfsBodemWaterPlan. Maatwerk voor duurzaam bodem en waterbeheer	www.bbwp.nl
Zwart	De organische stof balans met de te verwachten stikstoflevering per teeltrotatie	https://edepot.wur.nl/272649; www.os-balans.nl
Doorn	Biodiversiteitsmonitor akkerbouw	https://edepot.wur.nl/563407
SMK	On the way to planet proof - Melk	https://downloads.smk.nl/Public/Criteria%20On%20the%20way%20to%20PlanetProof%20melk%20M2.1_maart%202023.pdf
SMK	On the way to planet proof - Eieren	https://downloads.smk.nl/Public/PlanetProof_documenten/Melk/2022/Certificatieschema%20OPP%20Ei%20DP23.1_incl%20aanvullende%20besluiten%20tot%2019-9-2022.pdf
SMK	On the way to planet proof - Plataardige productie	https://downloads.smk.nl/Public/PlanetProof_documenten/Plantaardige%20producten%20(NL)/2023/NL%20-%20Certificatieschema%20On%20the%20way%20to%20PlanetProof%20Plantaardige%20Producten%20PP.5%20juni%202023.pdf
de Haan	Bodemindicatoren voor Landbouwgronden in Nederland	https://edepot.wur.nl/634579
Bastian	European Analytical Framework for the Development of Local Agri-Environmental Programmes	https://link.springer.com/article/10.1051/agro:2007027
Federaal Bureau for Agriculture (FOAG)	Agrarumweltmonitoring (AUI)	https://www.blw.admin.ch/blw/de/home.html
Solagro	Carbon Calculator	https://solagro.com/
Solagro	DIALECTE	https://dialecte.solagro.org/
Deutsche Landwirtschafts-Gesellschaft (DLG)	DLG-Nachhaltigkeits-Index	https://www.dlg-nachhaltigkeit.info/fileadmin/downloads/pdf/DLG-Nachhaltigkeits-Index_2018.pdf

Field to market	Continuous Improvement Accelerator	http://fieldtomarket.org/media/2021/12/Field-to-Market_2021-National-Indicators-Report_FINAL.pdf
INL GmbH	REPRO	https://nachhaltige-landbewirtschaftung.de
Dantsis	Dantsis	https://www.sciencedirect.com/science/article/abs/pii/S1470160X09000971
Thiollet-Scholtus	INDIGO	https://www.sciencedirect.com/science/article/abs/pii/S116103011400104X?via%3Dihub
Rodrigues	APOIA-NovoRural	https://www.sciencedirect.com/science/article/abs/pii/S0195925509001267
Aarts Van Dijk	ANCA	https://library.wur.nl/WebQuery/wurpubs/fulltext/407176 and https://edepot.wur.nl/582185
Pacini	AESIS	https://agronomy.it/index.php/agro/article/view/ija.2009.1.23
Calker	Development and application of a multi-attribute sustainability function for Dutch dairy farming systems	https://www.sciencedirect.com/science/article/abs/pii/S0921800905002636?via%3Dihub
Breitschluh	KSNL	https://www.umweltbundesamt.de/publikationen/folgenabschaetzung-einer-zunehmenden-bereitstellung
FAO	SAFA INDICATORS	https://www.fao.org/nr/sustainability/sustainability-assessments-safa/en/
Viglizzo	A Rapid Method for Assessing the Environmental Performance of Commercial Farms in the Pampas of Argentina	https://link.springer.com/article/10.1007/s10661-006-7981-y
Ros	An Open Soil Health Assessment Framework Facilitating Sustainable Soil Management	https://pubs.acs.org/doi/10.1021/acs.est.2c04516#
Conseil Scientifique de l'Environnement de Bretagne	Bilan Globale Azotée (Total Nitrogen Balance)	https://cseb-bretagne.fr/index.php/component/remository/func-startdown/1/?Itemid=167
Thalmann (project leader)	RISE 3.0: Response-Inducing Sustainability Evaluation	https://www.bfh.ch/hafl/en/research/reference-projects/rise/
Carof	SyNE	https://www.nefficiencycalculator.fr/en/ ; https://doi.org/10.1016/j.agsy.2018.01.015
Meul	MOTIFS	https://link.springer.com/article/10.1051/agro:2008001
CoolFarm	Cool Farm Tool - Plant Production Module	https://app.coolfarmtool.org/docs/api/quick-start.html#html-demo-tool

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