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# Achieving the nutrient reduction objective of the Farm to Fork Strategy. An assessment of CAP subsidies for precision fertilization and sustainable agricultural practices in Germany

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The Farm to Fork Strategy of the EU aims at sustainable food systems. One objective of the Strategy is to reduce nutrient losses by at least 50% resulting in at least 20% less fertilizer use by 2030. To this end, Member States are expected to extend digital precision fertilization and sustainable agricultural practices through the Common Agricultural Policy. In this context, this article applies a qualitative governance analysis which aims to assess the extent to which the measures proposed by the Farm to Fork Strategy, i.e., digital precision fertilization and sustainable agricultural practices, contribute to the nutrient objective of the Farm to Fork Strategy. The article analyses how these measures are implemented through the Common Agricultural Policy in Germany and Saxony. Results show that the nutrient objective of the Farm to Fork Strategy itself offers shortcomings. Germany offers some, yet overall limited, support for sustainable agricultural practices and digital precision fertilization. Hence, the Common Agricultural Policy will to a limited extent only contribute to the objective of the Strategy. The results furthermore highlight some general shortcomings of digitalization as sustainability strategy in the agricultural sector including typical governance issues (rebound and enforcement problems), and point to the advantages of quantity-based policy instruments.

## KEYWORDS

Farm to Fork Strategy, Common Agricultural Policy, precision fertilization, precision farming, digitalization, sustainable agriculture, agricultural subsidies, phosphorus

## 1. Introduction

Climate change and biodiversity loss put pressure on the agricultural sector. This pressure has recently increased due to rising resource and food prices and the war in the Ukraine (Ekardt and Rath, 2022; European Commission, 2022a). In fact, food security has moved to the top of the political agenda as grain exports from the Ukraine have basically come to a halt and fertilizer prices skyrocketed (The World Bank, 2022). To combat these issues, policy instruments are urgently needed which transition the agricultural sector away not only from fossil fuel dependency and intensive livestock farming but also from unsustainable nutrient management. Thereby, unsustainable nutrient management is connected with both, fossil fuel dependency and intensive livestock farming. Nitrogen (N) fertilizer production requires substantial amounts of fossil fuels (International Energy Agency, 2021). To a smaller extent, this also applies for Phosphorus (P) fertilizer production from phosphate rock as well as for recycled P fertilizers

(Garske, 2019; Jupp et al., 2021). Furthermore, environmentally-damaging P and N hotspots frequently occur in regions with intensive livestock farming (Rothwell et al., 2020; Withers et al., 2020). To overcome these challenges, for decades, calls have been made to fundamentally transform agricultural practices to become sustainable (e.g., Carson, 1962). In the recent past, these calls have been supplemented by great hopes in digital innovations (Ekardt, forthcoming; Lowry et al., 2019; Zhang et al., 2021; Ekardt and Rath, 2022; Maffezzoli et al., 2022). Digital innovations are expected to contribute to environmental protection by increasing resource and energy efficiency for example through digital precision fertilization. In doing so, digital innovations are expected to enable resource-extensive growth that combines economic and environmental aspirations (Balafoutis et al., 2017, p. 7–9; Rose and Chilvers, 2018; Lowry et al., 2019; Ekardt, 2020, chap. 1.4; Garske and Ekardt, 2021; Garske et al., 2021).

In this context, the EU Commission adopted the Farm to Fork Strategy. The Farm to Fork Strategy is one element of the European Green Deal (European Commission, 2020b). Both initiatives establish the framework for a sustainable transition across all sectors including the agricultural sector in the EU. They are legally non-binding Communications and expected to contribute to the goals of the Paris Agreement and the Convention on Biological Diversity. The Farm to Fork Strategy aims at food security, sustainable food value chains and sustainable nutrient management (European Commission, 2020a). It addresses environmental pollution caused by unsustainable nutrient management—in particular by N and P: The Strategy aims to reduce nutrient losses by at least 50%, while ensuring soil fertility, and reducing fertilizer use by at least 20% by 2030. To achieve this objective, the EU Commission aims at digital approaches, i.e., extending the application of digital precision fertilization, and sustainable agricultural practices. They are to be implemented through the Common Agricultural Policy (CAP) (European Commission, 2020a, p. 7–8).

Earlier research on the Farm to Fork Strategy provided comprehensive assessments (Schebesta and Candel, 2020), economic implications (Wesseler, 2022), (potential) impacts on the organic farming sector (Moschitz, 2021; Purnhagen et al., 2021), sustainable food consumption (König and Araújo-Soares, 2021) and animal welfare (Molitorisová and Burke, 2022). Others modeled the impact of the Strategy on input use including fertilizer input reduction in the EU (Beckman et al., 2022) and Italy (Cortignani et al., 2022). Input reduction is also discussed in light of its effects on food (in)security (Baquedano et al., 2022). Digital innovations are also analyzed (Reinhardt, 2022). Regarding the CAP, one study broadly investigates the Strategy's implementation through the CAP (Schebesta and Candel, 2020; Wesseler, 2022) while another discusses the implementation of the Strategy through the lens of policy integration in the second pillar of the CAP in Germany (Bazzan et al., 2022). Against this backdrop, this article aims to assess the extent to which the measures of the Farm to Fork Strategy, namely digital precision fertilization and sustainable agricultural practices, contribute to its nutrient objective, i.e., fertilizer input reduction and nutrient loss reduction. To this end, the analysis focuses on how these measures are implemented through the CAP in Germany. Saxony will serve as example for the second pillar of the CAP which is regulated at state level. In doing so, the present article extends the current research and offers new perspective by adopting an interdisciplinary governance analysis on sustainable nutrient management.

The following section describes the qualitative governance analysis. The section thereafter introduces digital precision fertilization and its potential to reduce fertilizer input and nutrient losses into the environment. We will not discuss sustainable agricultural practices and their potential to reduce fertilizer input and nutrient losses into the environment as we have extensively covered this topic in earlier publications (Garske, 2019; Stubenrauch, 2019). An overview of CAP measures which support the application of digital precision fertilization and measures which support sustainable agricultural practices in Germany follows. The discussion critically reviews the CAP measures in relation to the nutrient objective of the Farm to Fork Strategy and analyses this objective in the context of the goals of the Paris Agreement and the Convention on Biological Diversity. Conclusions follow.

## 2. Materials and methods

This article applies a qualitative governance analysis which aims to identify effective policy instruments to achieve a policy goal. The present qualitative governance analysis assesses policy instruments against the legally binding goals of the Paris Agreement and the Convention on Biological Diversity. The Paris Agreement aims to keep global warming “well below 2 °C above pre-industrial levels” and “pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” [Art. 2(1) Paris Agreement]. The Kunming-Montreal Global biodiversity framework aims at the maintenance and restoration of global ecosystems, and halting human induced extinction by 2050 (Goal A). The Convention on Biological Diversity aims to stop global biodiversity loss (Aichi Target B and C). Achieving these goals requires comprehensive transitions in the agricultural sector including in nutrient management which is, as indicated before, associated with various environmental issues such as eutrophication of water bodies and N<sub>2</sub>O emissions from agricultural soils (Tubiello et al., 2013; European Commission, 2021; Nessel et al., 2021; Refsnider et al., 2021). In turn, aligning the agricultural sector and nutrient management with the goals of the Paris Agreement and the Convention on Biological Diversity will limit manure for fertilization due to reduced livestock numbers, demand stopping fossil-based N fertilizer production and carefully using rock phosphate—being a scarce resource and primarily sourced for fertilizers (Garske, 2019; Stubenrauch, 2019; European Commission, 2020c, p. 80).

In this context, the qualitative governance analysis builds on findings from behavioral studies which shed light on typical governance problems such as shifting and rebound effects, enforcement and depicting problems, and lacking target stringency (Garske, 2019, p. 69–75; Ekardt, 2020, chap. 4.4; depicting problems in Smith et al., 2020; shifting effects in Jansson et al., 2020). Besides that, the qualitative governance analysis builds on findings from natural sciences. For the purpose of this article, we use our findings of earlier work on sustainable P management (Garske, 2019; Stubenrauch, 2019). In addition, we reviewed literature on digital precision fertilization. The aim of the literature review was to (1) provide an overview of digital precision fertilization and (2) understand their fertilizer savings potentials. As regards the second aim, we were looking for studies which assess the fertilizer reduction potential of digital precision fertilization in Germany. However, a first literature screening revealed that there were little to no

TABLE 1 Overview of legal documents.

EU level	CAP Strategic Plan Regulation (EU) 2021/2115 (CAPSpR); Commission's observation letter		
	First pillar		Second pillar
Federal level	GAP-Direktzahlungen-Gesetz (GAPDZG) <sup>a</sup>	GAP-Konditionalitäten-Gesetz (GAPKondG) <sup>b</sup>	Gesetz über die Gemeinschaftsaufgabe "Verbesserung der Agrarstruktur und des Küstenschutzes" (GAKG) <sup>c</sup>
	GAP-Direktzahlungen-Verordnung (GAPDZV) <sup>c</sup>	GAP-Konditionalitäten-Verordnung (GAPKondV) <sup>d</sup>	
State level			Draft fact sheet "Environmental, climate-related and other management commitments"
			Draft fact sheet "Investments"

<sup>a</sup>CAP Direct Payment Law. Access in German: <http://www.gesetze-im-internet.de/gapdzg/BJNR300300021.html>.

<sup>b</sup>CAP Conditionality Law. Access in German: <http://www.gesetze-im-internet.de/gapcondg/BJNR299600021.html>.

<sup>c</sup>CAP Direct Payment Ordinance. Access in German: <http://www.gesetze-im-internet.de/gapdzv/BJNR013900022.html>.

<sup>d</sup>CAP Conditionality Ordinance. Access in German: <https://www.gesetze-im-internet.de/gapcondv/BJNR224400022.html>.

<sup>e</sup>Law on the joint task. "Improvement of agricultural structure and costal protection". Access in German: <https://www.gesetze-im-internet.de/agrstruktg/BJNR015730969.html>.

studies. Therefore, we extended our search scope to include studies outside Germany. Google scholar served as starting point for the literature search. We used the search terms "precision agriculture, Germany"; "Präzisionslandwirtschaft, Düngung"; "precision agriculture, fertilization"; "precision agriculture, phosphorus" and "digitalization, agriculture, Germany". We screened the first 100 results of each search. Articles were included into our databank that either investigate the effects of precision agriculture with or without a focus on fertilization and soils in Germany or elsewhere as well as studies which provide an overview over precision farming techniques. We focused on peer-reviewed articles and book chapters since 2000. Going through the articles and book chapters, we frequently sourced their bibliography for further literature ("snowballing"). The results of the literature review are provided in Section 3.

The qualitative governance furthermore includes an analysis of legal acts and jurisprudence and their impact as well as opportunities for optimization. For this qualitative governance analysis, we build on earlier work on the reformed CAP (Heyl et al., 2021). In short, the CAP is the major agricultural policy of the EU and includes a comprehensive subsidy scheme which has been reformed multiple times during its six-decade long existence. In 2018, the most recent reform started and is currently in its final steps. The CAP will continue to consist of two pillars. The first pillar covers market management and income support. The hectare-based income support for farmers is conditional on compliance with the requirements of conditionality. Approximately one quarter of the first pillar budget is allocated to voluntary eco-schemes. The second pillar covers multi-year rural development programs. In February 2022, Germany submitted its Strategic Plan to the Commission which establishes the national implementation of the EU provisions (Federal Ministry of Food Agriculture, 2022). The EU Commission assessed the Strategic Plan and in May 2022, published its observation letter. In November 2022, the Commission approved the Strategic Plan (European Commission, 2022b).

This qualitative governance includes the following legal documents of the CAP (Table 1).

At the EU level, the CAP Strategic Plan Regulation (EU) 2021/2115 (CAPSpR)<sup>1</sup> establishes the framework for both pillars of the CAP. In Germany, the first pillar of the CAP is regulated

at the federal level. The national CAP laws ("Gesetze") of the first pillar were adopted by the German Parliament in summer 2021. The GAPDZG establishes the overall framework for the direct payments (income support) and the eco-schemes. The GAPKondG contains the rules on the standards for good agricultural and environmental condition of land which form one element of conditionality. The national CAP regulations ("Verordnungen") were adopted by the Federal Council in winter 2021. These regulations contain details for the implementation of the direct payments (GAPDZV) and conditionality (GAPKondV). The legal framework for second pillar implementation is established in the GAKG. The GAKG establishes that the second pillar is regulated at the state level. Saxony will serve as example for the present analysis. However, as the legislative process has not been completed, the analysis builds on draft fact sheets for investment and environmental support measures of the Saxon State Ministry for Energy, Climate Protection, Environment and Agriculture (<https://www.smekul.sachsen.de/foerderung/entwurfsdokumente-zum-gap-strategieplan-11,798.html>).

### 3. Overview and potentials of digital precision fertilization

Precision farming is based on processing detailed data to monitor and optimize agricultural production (Schrijver, 2016; Nair et al., 2021). Data can be provided by remote sensing applications. Remote sensing describes non-contact measurement of different parameters. Various sensor platforms can be used. For example, platforms include satellites and drones as well as tractors and hand-held instruments whereby the latter is sometimes called proximate sensing (Mulla, 2013; Segarra et al., 2020). These optical methods are based on measuring radiation after interacting, e.g., reflectance and absorption, with soils and plants. For precision farming in general, remote sensing combined with artificial intelligence, e.g., image recognition, can be used to identify farmland parcels (Dong et al., 2018). For fertilizer management in particular, data on soil and plant properties is needed (e.g., Laskar and Mukherjee, 2016; Ahmadi et al., 2021). There, remote sensing in combination with modeling or artificial intelligence is used to e.g., predict plant available P in soils thus enabling site specific fertilizer management (Dong et al., 2018; Erler et al., 2020, p. 10). However, some common approaches are not effective in sensing (plant available) P in soils such as near-infrared sensing (Kuang et al., 2012, p. 168–169; Soriano-Disla et al., 2014,

1 Access here: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R2115>.

p. 163; Laskar and Mukherjee, 2016; Leenen et al., 2022). Still, plant available P can indirectly be measured by investigating other soil properties, such as organic carbon, which correlate with plant available P. However, more research is needed to better understand these relationships (Stenberg et al., 2010, chap. 2.4; Kuang et al., 2012, p. 160–162, 197–198; Pätzold et al., 2020, p. 738–739). Yet overall, these approaches avoid labor and time-intensive conventional soil testing and consecutive analysis in laboratories (Bogrekci and Lee, 2005; Laskar and Mukherjee, 2016).

An application of optical and electrochemical sensing is the identification of crop nutrient status and fertilizer demand. For example, optical proximate sensors are used for leaf analysis to capture foliar P concentrations (Dao, 2017). Another approach is the calculation of vegetation indices (Xue and Su, 2017; Segarra et al., 2020, p. 5–7; Sishodia et al., 2020, p. 8–10; Oberti and Schmilovitch, 2021, p. 120–121). One index to estimate plant nutrient status is the normalized difference vegetation index. The index highlights differences in reflectance of crops on a parcel: Healthy vegetation reflects more radiation in the infrared spectrum compared to unhealthy vegetation. Algorithms convert the vegetation index into fertilizer application rates. In doing so, nutrient use efficiency can be increased and nutrient losses into the environment reduced (Maes and Steppe, 2019, p. 157–158; Sishodia et al., 2020, p. 8–10, 14–15; Rovira-Más and Saiz-Rubio, 2021). However, depending on the nutrient, the predictability of different indices varies (Mahajan et al., 2014, 2017). Another approach is the application of electrochemical sensing to measure nutrients in plants and soils. These sensors capture an electrical signal that results from a chemical reaction with the substance under investigation. The electrical signal offers insights about this substance (Kim et al., 2009; Kuang et al., 2012, p. 186–189; Nadporozhskaya et al., 2022). Overall, these methods provide valuable data to optimize nutrient management.

Overall, digital precision fertilization can reduce pressure on the environment by e.g., reducing nutrient losses into water bodies. A review discusses the effects of sensor-based applications for site-adapted N management on yield, N use efficiency, profitability and environmental protection. Reviewed studies show that N input can be reduced between 2 and 82%. However, in these studies, the effects of sensor-based applications are compared to different parameters, e.g., farmer application, models, regional fertilizer recommendation, which distorts the results including the relative benefit of sensor-based applications (Colaço and Bramley, 2018). Besides that, models for precision P management have been developed. For example, one model aims to optimize P application based on P soil reserves. The model integrates the links between soil P reserves and fertilization, and soil P reserves and P losses into waterbodies as well as economic and ecological factors. Results show that P input into water bodies could be reduced by 20–31% in different locations (Iho and Laukkanen, 2012). Lastly, research on machine learning develops algorithms which enable site-adapted management of land, including fertilization, by considering many environmental and managerial factors. An experiment finds that one algorithm was able to reduce N input by about one quarter after five learning years (Saikai et al., 2020). Experiments, models and algorithms highlight that nutrient losses into the environment can be reduced through digital precision fertilization. However, the scope of these benefits may be distorted.

Site-adapted (or variable-rate) fertilization aims to optimize plant nutrient supply. To this end, fully automated, partly automated or non-automated technologies are used (Essl et al., 2021, p. 48). Partly automated or non-automated technologies enable

precision fertilization based on prescription maps (sometimes called application maps). Partly automated technologies process these maps directly in board computers of tractors (ibid.; Balafoutis et al., 2017, p. 7–8). Prescription maps are created based on data from remote sensing, soil maps or soil samples. These maps contain information about how much fertilizer has to be applied in a specific location (Yang et al., 2016, p. 182–185). When prescription maps are based on soil samples, nutrient demand is approximated by interpolation or artificial intelligence as soil sampling cannot be done in every location of a parcel. For example, machine learning methods process large amounts of e.g., spatial data from remote sensing to estimate nutrient demand of crops in a specific location (European Commission, 2018, p. 10; Singh et al., 2020; Radočaj et al., 2022). Then, forward speed of a tractor or the valve position is adjusted according to the fertilizer amount specified by the prescription map. This approach works for mineral fertilizers as well as farm manure and slurry (Grisso et al., 2011; Calcante et al., 2015). Fully automated technologies do not require prescription maps but use real-time sensors to collect and process data *in situ* (Yang et al., 2016, p. 180–186; Balafoutis et al., 2017, p. 7). Tractors as well as robots can be used for fertilizer application (Fountas et al., 2020, p. 10–11). A study on fully automated technologies, i.e., sensor-based variable-rate fertilization, found an 8% reduction in the total amount of N that was applied on the fields compared to a constant fertilizer rate chosen by farmers, and approximately 25% less N losses into the environment (Scharf et al., 2011). Application of site-adapted fertilization is diverse and as such can principally offer suitable solutions for many farmers.

Overall, studies show that digital precision fertilization can increase resource efficiency through reduced fertilizer input and less nutrient losses into the environment. In doing so, digital precision fertilization can generally contribute to the nutrient objective of the Farm to Fork Strategy. Building on these insights, the following section discusses the national implementation of the CAP in Germany and the extent to which measures support digital precision fertilization and sustainable agricultural practices.

## 4. Digital precision fertilization in Germany's CAP implementation

The Farm to Fork Strategy lists multiple digital applications to achieve the nutrient objective. Relevant CAP instruments include the Farm Sustainability Tool for Nutrients, investments, advisory services and EU space technologies (European Commission, 2020a, p. 7–8). Access to fast broadband internet is a prerequisite for (extending) the application of precision farming including digital precision fertilization which is expected to reduce fertilizer use (ibid., p. 16). In Germany, these measures are implemented through the second pillar of the CAP. This section firstly discusses Saxony's support for investments and secondly support for knowledge transfer and farm advisory services, both of which can directly and indirectly support digital precision fertilization.

### 4.1. Precision fertilization: Investment support

EU Member States have to provide investment support under the second pillar of the CAP [Art. 69 lit. (d) CAPSpR]. Saxony

offers investment support for tangible and intangible assets that contribute to climate and environmental protection. For example, support is provided for investments into assets which reduce nitrate pollution in water bodies. This includes support for livestock farming and crop production such as environmentally-friendly manure storage, machinery for resource-saving manure application, and site-adapted fertilization. Besides that, support is provided for digitalizing business processes such as creating digital prescription maps which are a basis for site-adapted fertilization (Section 3) (Saxon State Ministry for Energy, 2022b, p. 7–8). These instruments can increase nutrient use efficiency by e.g., reducing fertilizer input and targeted fertilizer application. A reduction in nutrient hotspots which is caused by intensive livestock farming could furthermore be achieved by requiring recipients to have a livestock density of less than two livestock units per hectare (*ibid.*). This also benefits nutrient management, i.e., to better closed nutrient cycles.

Saxony furthermore provides support for investments which increase farm competitiveness in particular through modernization. This includes support for purchasing digitally supported machinery to e.g., mechanically manage weeds, for purchasing drones to apply insects for pest control, and for digitalizing business processes (*ibid.*, p. 9–10). While these measures do not directly target precision fertilization, they aim at pushing precision farming more broadly. At last, to enhance biodiversity, Saxony provides support for machinery and equipment for conservation management and maintenance (*ibid.*, p. 17) which can indirectly contribute to sustainable nutrient management by e.g., enhancing soil biodiversity.

## 4.2. Precision fertilization: Knowledge exchange and advisory services

Support for advisory services and knowledge transfer can directly and indirectly push digital precision fertilization (and farming). Member States of the EU are required to offer farm advisory services which include up-to-date technological information. Assistance must be offered for innovative practices and agricultural techniques for resilience to climate change [Art. 15(2) CAPSpR]. Farm advisory services have to cover digital technologies in agriculture and sustainable management of nutrients, including the use of a digital Farm Sustainability Tool for Nutrients from 2024 onwards [Art. 15(4) lit. (f), (g) CAPSpR]. The tool has to provide a balance of the main nutrients at field scale, legal requirements on nutrients, soil data, and data from the integrated administration and control system relevant for nutrient management [Art. 15(4) lit. (g) CAPSpR]. This tool could serve as a basis for digital precision fertilization (Section 3). However, the Farm Sustainability Tool for Nutrients is currently neither covered explicitly in Germany's CAP Strategic Plan nor in the second pillar measures of Saxony.

Member States furthermore have to provide support for knowledge exchange and dissemination of information [Art. 69 lit. (h) CAPSpR]. Saxony provides support for conferences, events, trainings, workshops and working groups, expert excursions and demonstration projects which cover land management and measures to minimize substance discharge in priority areas of the Water Framework Directive 2000/60/EC, to minimize fertilizer input and to reduce soil erosion and promote soil protection in general (Saxon State Ministry for Energy, 2022b, p. 30). These events could

contribute to expand the application of digital precision fertilization in Saxony.

Overall, Saxony's second pillar measures support digital precision fertilization. However, while some measures directly address site-adapted fertilization, most programs broadly aim at farm modernization and innovation. Besides, the extent to which support for advisory services and knowledge transfer will address digital precision fertilization will ultimately depend on the actual events that will receive funding.

## 5. Sustainable agricultural practices in Germany's CAP implementation

Alongside digital precision fertilization, the Farm to Fork Strategy considers sustainable agricultural practices for achieving the nutrient objective. Both pillars of the CAP support sustainable agricultural practices. First pillar measures include the requirements of conditionality, which is made up of statutory management requirements (SMRs) and standards of good agricultural and environmental conditions of land (GAEC standards). Besides, some eco-schemes support sustainable agricultural practices which are beneficial for the nutrient objective of the Farm to Fork Strategy. Second pillar measures include in particular agri-environment-climate commitments.

The requirements of conditionality impact nutrient management directly and indirectly. Table 2 provides an overview of nutrient relevant requirements of conditionality and their effects on nutrient management. Some requirements such as SMR 1, SMR 2 and GAEC 4 directly address P and N management while other requirements cover sustainable soil management which have an indirect impact on nutrient management, e.g., minimum soil cover (GAEC 6) and crop rotation (GAEC 7). These requirements can principally reduce fertilizer demand, limit nutrient losses into the environment, and improve monitoring of nutrient management.

Eco-schemes are a new CAP instrument, some of which impact nutrient management. In general, support is provided for annual voluntary agricultural practices that are beneficial for climate, environment and animal welfare (Art. 18 GAPDZG). These practices have to go beyond the requirements of conditionality and other legal requirements on e.g., fertilization [Art. 31(5) lit. (a), (b) CAPSpR]. Germany allocates 23% of the first pillar budget for eco-schemes [Art. 15(1) GAPDZV], and offers seven eco-schemes (Art. 20 GAPDZG) whose details are established in the GAP-Direktzahlungen-Verordnung (GAPDZV). One nutrient-relevant eco-scheme covers support for the extensification of permanent grassland. Support is provided for holdings which have a livestock density of 0.3–1.4 livestock units per hectare. Fertilizer application is limited to the extent which corresponds to the manure of 1.4 livestock units per hectare [Art. 20(1) No. 4 GAPDZG i.c.w. Annex 5 No. 4 GAPDZV]. Hence, nutrient input into the environment can be reduced. Another nutrient-relevant eco-scheme covers the cultivation of diverse crops including 10% legumes. A minimum of five different crops must be grown on at least 10% and at most 30% of the arable land. Grains must not be cultivated on more than 66% of the arable land (Art. 20(1) No. 2 GAPDZG i.c.w. Annex 5 No. 2 GAPDZV). Legumes can fix nitrogen and supply it to plants (Hillel, 2008, p. 155; Blume et al., 2016, p. 102; Stagnari et al., 2017). Thus, N fertilizer demand can be reduced. Besides, when legumes are used as

TABLE 2 Nutrient relevant requirements of conditionality.

	Requirement details		Effects on nutrient management
Statutory management requirements (SMRs)	SMR 1	<b>Control of diffuse sources of pollution by phosphates</b> Measures to prevent or control the input of phosphates into river basin districts, e.g., prior authorization or registration. (Art. 3(1) No. 1 GAPKondG i.c.w. Annex II CAPSpR i.c.w. Art. 11(3) lit. (h) Directive 2000/60/EC)	Monitors and reduces excess phosphates into water bodies.
	SMR 2	<b>Protection of water bodies against nitrate pollution</b> Establishment of voluntary (cod) s) of good agricultural practice, and action programs for designated vulnerable zones. (Art. 3(1) No. 1 GAPKondG i.c.w. Annex II CAPSpR i.c.w. Art. 4 and 5 Council Directive 91/676/EEC)	Reduces nitrate input into water bodies.
Standards of good agricultural and environmental conditions of land (GAEC standards)	GAEC 4	<b>Buffer strips along water courses</b> Establishment of buffer strips alongside agricultural areas with a minimum width of three meters, fertilizer application is prohibited. Exemptions are established for certain water bodies. (Art. 15 GAPKondV i.c.w. Annex II CAPSpR)	Reduces nutrient runoff into water bodies (Sidemo-Holm et al., 2018; Stutter et al., 2019).
	GAEC 5	<b>Tillage management to reduce soil erosion</b> Plowing on agricultural land at risk of water erosion is prohibited in winter and partly restricted in other seasons. (Art. 16(1)(2) GAPKondV i.c.w. Annex II CAPSpR)	Contributes to reduce nutrient losses through wind and soil erosion into the environment (Alewell et al., 2020).
	GAEC 6	<b>Minimum soil cover</b> Having a minimum soil cover in winter for example, i.e., catch crops, winter crops or stubble fields. (Art. 17(1) GAPKondV i.c.w. Annex II CAPSpR)	Reduces fertilizer demand: Deep rooting catch crops benefit erosion control, enhance soil structure which fosters soil water transportation. As plants can only adsorb dissolved phosphate, enhanced water transportation also benefits P transportation and thus P uptake of plants (Hillel, 2008, p. 70–77; Blume et al., 2016, chap. 9.5).
	GAEC 7	<b>Crop rotation</b> Mandatory requirement on arable land. Exempted are multiannual crops and holdings with < 10 hectares arable land. Further exemptions can be established by state governments. (Art. 18 GAPKondV i.c.w. Annex II CAPSpR)	Reduces fertilizer demand: Contributes to soil fertility by enhancing soil biodiversity and by making P plant available (Venter et al., 2016; Uzo et al., 2019).
	GAEC 8	<b>Non-productive areas</b> 4% of arable land must be devoted to non-productive areas. Non-productive areas must lie fallow throughout the year. Fertilizer application and removal of landscape elements are prohibited. Exemptions are established for e.g., holdings with more than 75% permanent grassland and holdings with < 10 hectares arable land. (Art. 19-23 GAPKondV i.c.w. Annex II CAPSpR)	Reduces nutrient losses through wind erosion (Borrelli et al., 2016; Xiao et al., 2021a).

catch crops, they benefit the prevention of erosion and improve soil structure, thus avoid P losses and potentially enhance P availability for plants (Eichler-Löbermann et al., 2016; Vitow et al., 2021).

Agri-environment-climate commitments of the second pillar can also contribute to the nutrient objective of the Farm to Fork Strategy. These measures differ from eco-schemes by their multi-annual length. Still, eco-schemes and agri-environment-climate commitments can be combined. For some agri-environment-climate commitments, such as result-based payments for grassland management, participation in an eco-scheme is a mandatory prerequisite (Saxon State Ministry for Energy, 2022a, p. 25). In Saxony, agri-environment-climate commitments are divided into support for arable land, support for grassland, support for organic farming and compensatory allowances. Figure 1 provides an overview of one measure of each category—except for compensatory allowances—which impact nutrient management.

Overall, both pillars of the CAP support sustainable agricultural practices which can directly and indirectly contribute to the nutrient objective of the Farm to Fork Strategy. Two measures are voluntary (eco-schemes and agri-environment-climate commitments), one measure (conditionality) is mandatory. They address nutrient management differently, for example by reducing fertilizer demand,

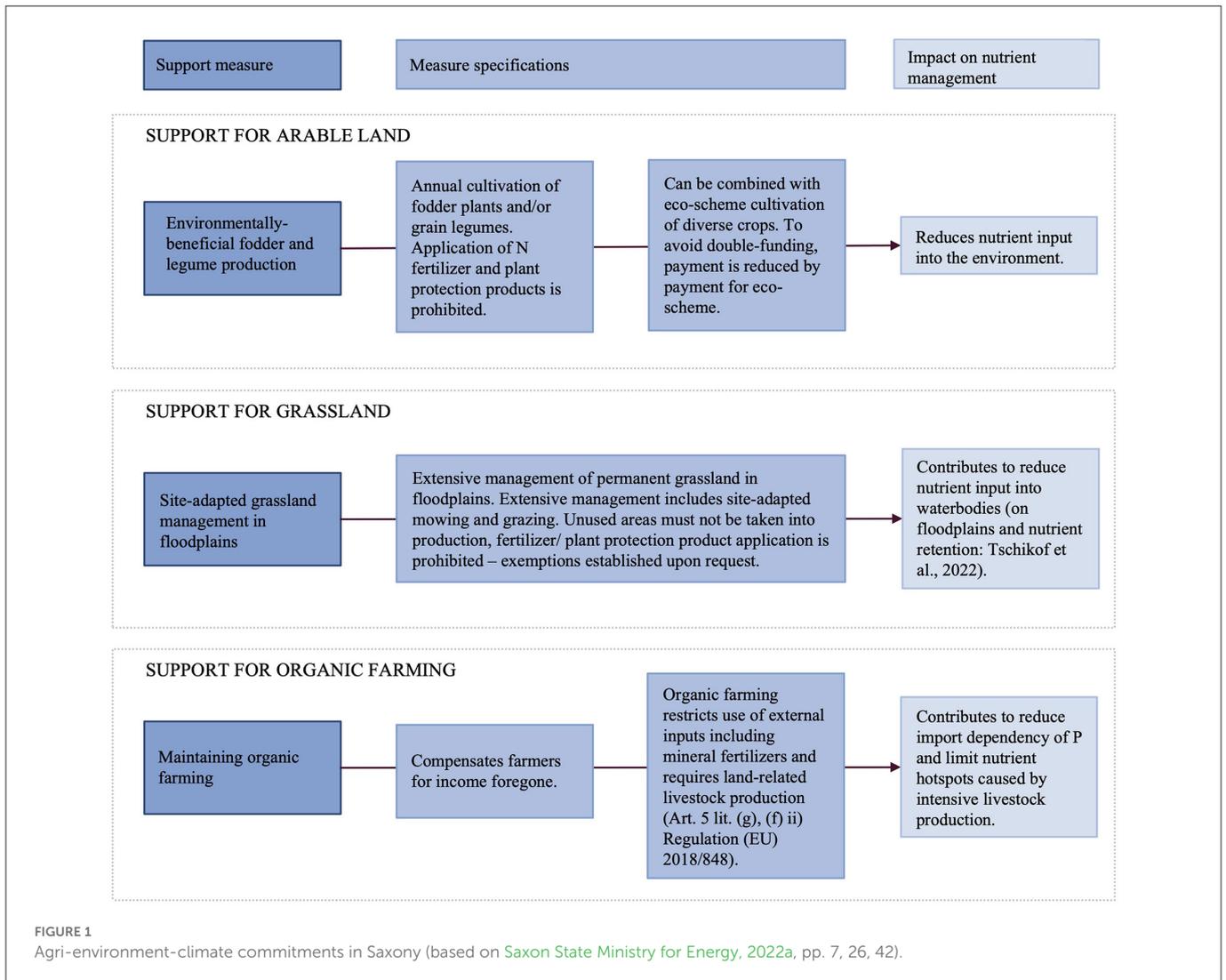
limiting nutrient losses into the environment and enhancing nutrient monitoring. Whether or not they provide effective means to achieve the nutrient objective of the Farm to Fork Strategy is discussed in the second part of the following section.

## 6. Discussion

### 6.1. Critical assessment of the measures and objective of the Farm to Fork Strategy

This section assesses the two measures, i.e., support for digital precision fertilization and sustainable agricultural practices, against the nutrient objective of the Farm to Fork Strategy. Besides, these measures and the Strategy itself are assessed against global environmental goals (Section 2).

Environmental challenges such as disrupted/open nutrient cycles, climate change and biodiversity loss require addressing the major drivers of these challenges, i.e., fossil fuels and intensive livestock farming (Weishaupt et al., 2020; Garske and Ekardt, 2021, p. 245; Stubenrauch et al., 2021, p. 716; van Asselt, 2021; e.g., Eisen and Brown, 2022). In this context, the Farm to Fork Strategy aims to



transform the food system of the EU which points in the right direction. In aiming to close P cycles, the Strategy not only addresses open nutrient cycles but also biodiversity loss (Section 1). For example, biodiversity is improved if P fertilization was adjusted to soil properties and plant demand and hence eutrophication of water bodies limited (Section 2). Likewise, in aiming to close N cycles, the Strategy not only addresses open nutrient cycles but also greenhouse gas emissions. Greenhouse gases are reduced if fossil-based N fertilizer was eliminated, livestock farming substantially downscaled and thus manure limited and eutrophication limited. However, the Farm to Fork Strategy fails to target the drivers of environmental pollution when it calls for extending digital precision fertilization and sustainable agricultural practices notably in regions with intensive livestock farming (European Commission, 2020a, p. 8). In doing so, the Farm to Fork Strategy addresses the symptoms of environmental pollution rather than targeting the driver of excess nutrients, i.e., high livestock intensity. As such, this approach will have—if at all—a very limited steering effect.

Likewise, the Farm to Fork Strategy touches upon managing the entire nutrient cycle but effective actions appear unlikely. Sustainable nutrient management is not only an agro-ecological challenge but requires integrated solutions along the entire value chain (Withers et al., 2020; Bieroza et al., 2021). For example, at the beginning

of the value chain, P fertilizer production creates radioactive by-products (United States Environmental Protection Agency, 2021). At the end of the value chain, diets have different P intensities (Forber et al., 2020; Papangelou et al., 2021). The Farm to Fork Strategy points to an integrated nutrient management action plan ‘to address nutrient pollution at source’ (European Commission, 2020a, p. 8), but many aspects of nutrient management remain unconsidered. Moreover, as Communication, the integrated nutrient management action plan will not be legally-binding and hence also have a limited steering effect.

At last, the general objective of reducing nutrient losses by at least 50% resulting in at least 20% less fertilizer use by 2030 offers shortcomings (see also Bieroza et al., 2021, p. 3–5). Focusing only on P fertilizers containing rock phosphate (and N fertilizers produced by the Haber-Bosch process) bears the danger of shifting effects: Manure could replace nutrient supply from fertilizers containing rock phosphate (proposed by delegations at the Council of the European Union, 2022). While this would limit the import dependency of rock phosphate, nutrient hotspots will remain. These nutrient hotspots would have to be addressed by a supplementary livestock-to-land ratio. However, only adopting a livestock-to-land-ratio will to a limited extend only address greenhouse gas emissions and biodiversity issues of livestock farming. Instead, if the drivers of

environmental pollution were addressed at EU level by (1) extending the Emissions Trading System with an emission cap zero by 2030 (Ekardt et al., 2018, 2022; Ekardt, 2020, chap. 4) and (2) implementing emission trading for livestock products (Weishaupt et al., 2020), livestock numbers were reduced and nutrient losses automatically downscaled (but) without a specific reduction rate. Reduced livestock numbers will limit manure supply, but a livestock-to-land ratio is still needed for nutrient hotspots. The advantage of targeting the drivers of climate change and biodiversity loss instead of focusing only on nutrient management is that this approach tackles the intertwined global challenges simultaneously and hence contributes to achieving the goals of the Paris Agreement and the Convention on Biological Diversity. If these policies instruments were adopted, nutrient supply would depend on the extent to which mineral fertilizers could be produced with renewable energies, and the extent to which policy instruments push P recycling (Garske and Ekardt, 2021). These conditions will virtually lead to nutrient loss reductions by at least 50% (probably more) and hence to achieving the objective of the Farm to Fork Strategy. However, it remains an open question whether further support for digital precision fertilization and sustainable agricultural practices would be required *in addition to* measures which address the major drivers of environmental pollution—given that a ETS for the major drivers as such makes precision farming more attractive. In any case, failing to address fossil fuels and intensive livestock farming impedes achieving the nutrient objective of the Strategy—and the goals of the Paris Agreement and the Convention on Biological Diversity. Measures, whether digital (precision fertilization) or not (sustainable agricultural practices), will then miss the mark.

## 6.2. Critical assessment of Germany's CAP Strategic Plan

The Farm to Fork Strategy aims to establish a sustainable food system in the EU—alongside the EU's major agricultural policy, the CAP. However, the CAP has been criticized for its catastrophic impact on the environment for decades and the recent reform does not mark a turnaround (Scown and Nicholas, 2020; European Court of Auditors, 2021; Heyl et al., 2021; Scheffler et al., 2022). It is thus unsurprising that Germany's Strategic Plan of the reformed CAP reflects the longstanding inadequacies of the agricultural subsidies. Therefore, developments like ongoing soil degradation in the EU (Panagos et al., 2021) are likely to progress and will not only negatively affect nutrient cycles but also contribute to climate change and biodiversity loss. The reformed CAP thus clearly stands against the goals of the Paris Agreement and the Convention on Biological Diversity. In this context, the Commission's assessment of Germany's Strategic Plan required amendments (Art. 118 CAPSpR). In fact, the Commission requested Germany to establish a clearer alignment of the Strategic Plan with the Farm to Fork Strategy (European Commission, 2020a, p. 5). However, substantial improvements of the Strategic Plan are unlikely as the national legislative process has been completed.

The following section discusses the limited support for sustainable agricultural practices in Germany's CAP Strategic Plan. The section thereafter assesses the support for digital precision fertilization to then draw some general conclusions on the limitations

of digitalization as a purely technical strategy for a sustainable transition in the agricultural sector.

### 6.2.1. Limited support for sustainable agricultural practices

CAP support for sustainable agricultural practices is limited and unable to counteract the damaging impact of e.g., hectare-based income support with its weak environmental requirements. This is unfortunate as sustainable agricultural practices can support soil protection and soil biodiversity and thereby contribute to close nutrient cycles, and benefit climate and biodiversity (Jian et al., 2020; Köninger et al., 2021; Redlich et al., 2021; Xiao et al., 2021b). In doing so, these practices could support achieving the Farm to Fork objective and global environmental goals. Still, the voluntary measures of the CAP contain some promising instruments to support sustainable agricultural practices including on nutrient management. For example, the eco-schemes of the first pillar will likely reduce nutrient losses into the environment (Section 5). However, the effectiveness of eco-schemes is limited by their annual length as some impacts require multiple years to occur (Russi et al., 2016; Lønborg and Markager, 2021). Limited length is not an issue of the agri-environment-climate commitments of the second pillar which take multiple years. Instead, these programs are limited by substantial funding cuts (Nègre, 2022). Above all, both measures suffer from unclear uptake due to their voluntariness. Besides, a general issue of CAP subsidies is that they fail to incentivize landscape-scale adoption for example because of missing collaboration between different stakeholders (Leventon et al., 2017; Manolache et al., 2020; Berthet et al., 2021; Falco et al., 2021). Landscape-scale (or catchment-scale) adoption has been called for to reduce nutrient losses into the Baltic Sea (Bitschofsky and Nausch, 2019; Bierzo et al., 2021). These approaches could not only enhance effectiveness but also limit potential shifting effects. To counteract these shortcomings, a complete restructuring of CAP subsidies (toward the provision of public goods) is needed.

The steering effect of conditionality on nutrient management is limited as well. The effectiveness of these requirements is limited by multiple exemptions (GAEC 4,7,8), voluntariness (SMR 2) and very limited controls of a minimum of 1% of subsidy recipients [Art. 16(1) GAPKondG]. Moreover, concerns about food security due to the war in the Ukraine have recently led to a dilution of GAEC 7 (crop rotation) and GAEC 8 (non-productive areas) (Commission Implementing Regulation (EU) 2022/1317). Apart from that, Germany does not use its flexibility to implement ambitious standards under conditionality. A comparatively high environmental protection standard could have been achieved if Germany had oriented national standards toward the upper end of EU policy leeway. However, Germany frequently only adopts the minimum requirements. The establishment of buffer strips along water courses offers one example. According to EU provisions, farmers have to establish buffer strips with a minimum width of three meters (Annex III CAPSpR). Germany adopts this minimum requirement (Section 5). However, studies show that a limited buffer strip width limits P retention capacity (Sidemo-Holm et al., 2018, p. 212–213; see also Dal Ferro et al., 2019). Hence, a buffer strip width of three meters will have a limited effect on reducing P losses and on the nutrient objective of the Farm to Fork Strategy. It is thus good to see that the Commission picked up this issue in its observation letter and demands an explanation on the limited width. Another example

of the limited environmental protection ambitions of Germany concerns the eco-scheme's budget. EU provisions require a minimum budget for the eco-schemes (Art. 31 CAPSpR i.c.w. EU-document 10217/21). Again, Germany orients national implementation at the minimum requirements. However, in its observation letter, the Commission does not even see these minimum requirements fulfilled. The Commission demands a budget increase (European Commission, 2022a, p. 3). Overall, while the CAP Strategic Plan of Germany contains support for sustainable agricultural practices, this support is limited. Sustainable agricultural practices under the reformed CAP will thus to a limited extent only contribute to the nutrient objective of the Farm to Fork Strategy.

### 6.2.2. Policy issues of support for digital precision farming

While quantity-based policy instruments virtually redirect nutrient management toward sustainability (Section 6.1), CAP subsidies on precision fertilization are unlikely to induce such a development (Heyl et al., 2022). Saxony supports investments which contribute to climate and environmental protection such as investments into resource-saving manure application and site-adapted fertilization (Section 4). However, how to ensure that these investments will clearly contribute to climate and environmental protection – rather than environmental degradation – remains an open question. Besides, typical governance problems of these subsidies such as rebound and shifting effects are likely (Section 2). For example, the application of digital technologies in the agricultural sector is frequently associated with production extension and intensification due to efficiency gains (Schieffer and Dillon, 2015; Garske et al., 2021). Moreover, instruments that address single products, actions or sites like CAP subsidies suffer from enforcement issues and substantial administrative burden. While Member States may use remote sensing or an area monitoring system to check compliance with conditionality (Art. 83(6) lit. (c) Regulation (EU) 2021/2116), thus use digital technologies to limit these governance issues, their actual application could be further extended (José Martínez, 2019; Pe'er et al., 2019). Hence, these subsidies will to a limited extent only contribute to the nutrient objective of the Farm to Fork Strategy.

A promising proposal of the reformed CAP was the inclusion of a digital Farm Sustainability Tool for Nutrients in conditionality (Art. 12(3) CO (2018)392 final). As standard of good agricultural and environmental conditions of land, the application of this tool would have been compulsory to receive income support under the first pillar of the CAP (Section 2). However, Germany successfully pushed for the removal of the tool from conditionality (German Bundestag, 2020). Now, the tool is adopted as voluntary farm advisory service (Section 4) which drastically limits its steering effect and thus its contribution to the nutrient objective of the Farm to Fork Strategy.

### 6.3. Limitations of digitalization as technical sustainability strategy

The findings above lead to some general implications on digitalization as sustainability strategy in the agricultural

sector. Digital precision fertilization practices like sensor-based measurement of soil properties (Section 3) enable or simplify efficient and site-adapted fertilization and thus contribute to reduce nutrient input into the soil and nutrient losses into the environment. However, “precise” does not always mean “less”. Besides, digital precision fertilization is useless in regions with intensive livestock farming and corresponding nutrient hotspots due to manure excretion (Section 6.1). As such, the application area of digital precision fertilization is limited, and hence their geographical contribution to the nutrient objective of the Farm to Fork Strategy. Moreover, the potentials of remote sensing to optimize fertilization management is frequently overestimated (Colaço and Bramley, 2018), and applying artificial intelligence offers further challenges. For example, algorithms can be guided by different objectives such as reducing fertilizer input, minimizing environmental impacts or improving fertilization profitability. The latter objective demands maximum yields in relation to financial input which is likely to induce negative environmental impacts (see e.g., Saikai et al., 2020; Tzachor et al., 2022). Therefore, to contribute to the nutrient objective of the Farm to Fork Strategy, digital precision fertilization must clearly aim at fertilizer reduction and nutrient loss minimization.

Overall, great hopes are placed into the digitalization of the agricultural sector. These hopes reflect a widely shared expectation that digital applications can—as purely technical and efficiency-oriented strategy—achieve global environmental goals (Ekardt, 2020, chap. 1.3). However, the complexity of climate change, biodiversity loss (and nutrient cycling) counteracts these expectations. Still, digitalization offers many potentials to transition the sector toward sustainability but these potentials frequently come with substantial governance problems (see above). In general, the digitalization in the agricultural sector must not lead to an expansion of land for agricultural production but lead to an expansion of land for biodiversity. To this end, livestock farming has to be reduced due to its land and resource intensity (Weishaupt et al., 2020). Overall, the complexity of the environmental challenges and the efforts it requires to achieve the goals of the Paris Agreement and Convention on Biological Diversity will most likely require voluntary or politically-induced sufficiency. This applies to digitalization and all other areas of society. The proposed quantity-based instruments will induce technological efficiency and consistency as well as sufficiency and thus achieve the goals of global environmental agreements.

## 7. Conclusions

The Farm to Fork Strategy aims at sustainable food systems. To this end, the Farm to Fork Strategy objective is to reduce nutrient losses by at least 50% resulting in at least 20% less fertilizer use by 2030. Digital precision fertilization and sustainable agricultural practices are expected to contribute to this nutrient objective. Support for these measures is provided through the CAP. In this context, this article aimed to assess the extent to which the national implementation of the CAP in Germany provides support for digital precision fertilization and sustainable agricultural practices. While results highlight some fundamental issues of the nutrient objective of the Farm to Fork Strategy, the Strategy generally points in the

right direction. Besides, the CAP as implementing instrument of the nutrient objective principally provides some support for sustainable agricultural practices under both pillars. The adoption of the voluntary eco-schemes in particular is a welcome addition. Like agri-environment-climate commitments, these measures can be beneficial for sustainable nutrient management and hence contribute to the nutrient objective of the Farm to Fork Strategy. At the same time, the effectiveness of these measures is limited by limited length (eco-schemes), reduced budget (agri-environment-climate commitments) and voluntariness (both measures). Besides, Germany frequently adopts only minimum requirements for the receipt of income support (conditionality) which further limits the contribution of CAP support to the nutrient objective of the Farm to Fork Strategy. Support for digital precision fertilization is provided under the second pillar of the CAP. However, these subsidies suffer from typical governance issues. Besides, digital precision fertilization will only contribute to the nutrient objective of the Farm to Fork Strategy when (1) clearly aligned with fertilizer reduction and nutrient loss minimization and (2) combined with quantity-based policy instruments which target the major drivers of global environmental challenges, i.e., fossil fuels and livestock farming. Currently, CAP subsidies fail to address these drivers. In doing so, these subsidies will to a limited extent only contribute to the nutrient objective of the Farm to Fork Strategy and the goals of the Paris Agreement and the Convention on Biological Diversity. Therefore, these subsidies have to be restructured toward the provision of public goods only.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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## Author contributions

KH: conceptualization, methodology, formal analysis, writing—original draft preparation, and writing—review and editing. FE: methodology, writing—review and editing, and supervision. PR: background and formal analysis. BG: formal analysis and writing—review and editing. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

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