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Full length article

Contribution of livestock to organic agriculture: Modelling nitrogen flows at the national scale

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ABSTRACT

Organic agriculture (OA) is the promoted sustainable agriculture model in the European Union (EU), yet its expansion is hindered by limited nutrient availability, particularly nitrogen (N). OA's main sources of N include biological N fixation by legume crops and manure from both conventional and organic livestock. However, potential stricter EU regulations on allowed external N resources for OA and pressure to reduce livestock numbers could impact N availability in OA. Understanding national-scale N flows is essential. Here, we analysed N flows in organic agri-food systems in France, the largest OA area in Europe. We show that approximately 20 % of the manure used to fertilise organic cropland came from conventional agriculture and 15 % from the dietary N nutritional requirements of organic livestock imported from outside France. N surplus is half that of the conventional agriculture at national scale. This first national assessment highlights biophysical and regulatory constraints providing insights into the possibilities of achieving the EU's target of having 25 % of agricultural land under OA.

1. Introduction

To address the urgent environmental and climate challenges (Gills and Morgan, 2019), agri-food systems must undergo a large-scale transition to sustainably feed the global population, reduce reliance on non-renewable resources and preserve ecosystems. Organic agriculture (OA) is frequently advocated as a viable pathway for addressing these issues (Barbieri et al., 2021). The European Union's (EU) action plan (2021/2239(INI)), as part of its "Green Deal" policy, works to move towards a sustainable food system. The aims are to reduce nutrient surpluses by at least 50 %, reduce fertiliser use by at least 20 % and have at least 25 % of the EU's agricultural land under OA by 2030, compared to the current 9.9 % (EC, 2020). OA prohibits the use of synthetic fertilisers and promotes more sustainable food consumption, as required by agricultural policies (EC, 2020). OA is defined as a certified system of agricultural production (Parrott et al., 2006; IFOAM, 2021), that used agricultural practices based on ecological cycles (Gomiero et al., 2011). Among the advantages of OA, some studies have highlighted its lower impacts on biodiversity than those of conventional agriculture (Bengtsson et al., 2005; Seufert and Ramankutty, 2017).

Nevertheless, several hurdles to the development of OA have been identified, such as weed, pest and disease control (Halweil, 2006; Benoit et al., 2017), as well as economic and social barriers (Reganold and Wachter, 2016; Chatellier, 2024). Nitrogen (N), phosphorus (P), potassium (K) and micronutrients are essential nutrients for plant growth and crop quality (Einarsson, 2024). However, excessive use of nutrients, especially N and P, generates large surpluses, causing major changes in biogeochemical cycles (Drinkwater and Snapp, 2007; Sutton et al., 2011; Mahmud et al., 2021). In OA, one challenge is to reduce nutrient surpluses, while ensuring sufficient nutrient supplies (Connor, 2008). The supply of micronutrients and K in OA can be increased mainly by ensuring a continuous supply of organic matter to the soil (Stockdale et al., 2002), such as animal manure (Oelofse et al., 2013), or other amendments authorised in OA. Livestock manure also contains P, whose concentration depends mainly on the source of the manure, livestock housing and manure collection and storage systems (Van Faassen and Van Dijk, 1987). However, most agricultural P originally comes from mined phosphate minerals concentrated in a few countries (Demay et al., 2023; Einarsson, 2024), which makes P a limited resource over the long term. In the short term, N is the nutrient that limits the expansion of OA (Muller et al., 2017; Barbieri et al., 2021; Billen et al., 2021). In OA, the N supply comes mainly through biological N fixation (BNF) (Oelofse et al., 2013). At the farm scale, the main way to increase BNF is to increase the percentage of legume crops through longer crop rotations and

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associations (Barbieri et al., 2023). The second largest potential N input is the recycling of N flows from grassland to cropland by livestock (Berry et al., 2002; Peyraud et al., 2012; Dumont et al., 2016). In the EU, only fertilisers and soil conditioners authorised in OA and listed in Annex II of Regulation (EU) (2018/848) may be used, which limits N availability. The EU authorises use of manure from conventional agriculture in OA as long as it does not come from industrial livestock farms (Annex II Regulation (EU) (2018/848)) (Supplementary Organic regulations), and it can be a largest source of N in OA according to Kirchmann and Bergström (2008), Nowak et al. (2013b) and Nesme et al. (2016). These studies quantified nutrient inputs from conventional agriculture at the farm scale (Nowak et al., 2013b; Oelofse et al., 2013) but no study has yet illustrated OA's dependence on nutrients from conventional agriculture at the national scale. Furthermore, EU member states have adopted various regulatory positions (Table S1) to develop OA and its self-sufficiency by gradually limiting exceptions for the use of conventional manure. Reliance on nutrients from conventional sources may thus become a biophysical and regulatory limitation on future growth (Beck et al., 2014; Reimer et al., 2023).

In Europe, the numbers of all livestock species have decreased over the past 10 years. In 2022, there were 134 million pigs (–5 % since 2021), 75 million cattle (-1 %), 59 million sheep (-2 %) and 11 million goats (-3 %) (Eurostat, 2023). In addition, several agri-food scenarios at multiple scales indicate that livestock numbers must decrease greatly to maintain the availability of sustainably produced food (Van Zanten et al., 2018), increase nutrient circularity and reduce greenhouse gas emissions (van Selm et al., 2022) or to maintain the agri-food system within environmental limits (Springmann et al., 2018). Other studies have explored scenarios of complete conversion to OA or agro-ecological agriculture to estimate their impacts on N cycling at the global scale (Muller et al., 2017; Barbieri et al., 2021; Chatzimpiros and Harchaoui, 2023) or European scale (Billen et al., 2021). The two common drivers in these scenarios were including more legumes in crop rotations, and shifting human diets toward less consumption of animal protein, which may lead to a decrease in livestock numbers. Another specific driver was the recycling of human excreta (Billen et al., 2021; Chatzimpiros and Harchaoui, 2023), which is not authorised in OA. In all these scenarios, livestock numbers were set smaller than the current numbers, but in OA, whose N resources are limited, livestock seem necessary as a source of N via manure and must be considered (Barbieri et al., 2021).

A recent study estimated that a large percentage of OA farms in Europe rely on external sources of N from conventional agriculture through livestock manure (Reimer et al., 2023). However, potentially stricter EU regulations on the amount of sources of external N resources that can be used in OA and the increasing pressure to decrease livestock numbers already underway in some countries risk decreasing the availability of N in OA. As this challenge has barely been studied in the literature it is critical to examine the current N budget in OA based on the use of resources from livestock and quantify the degree of dependence on external N resources. The main studies on material flows (i.e. N, P and K) in OA have been performed at the farm scale (Berry et al., 2003; Nesme et al., 2012; Nowak et al., 2013a; Reimer et al., 2023). No study has considered OA at the national scale, or the biophysical and regulatory constraints that will exist if OA is to develop at large-scale. The present study focused on metropolitan France, which has the largest area of OA among countries in Europe (FiBL, 2023). It addressed these research gaps by (i) assessing N flows in OA at the national scale, (ii) estimating the contribution of livestock to the N circularity of OA and (iii) quantifying OA's dependence on external N sources. This study contributes to the debate on future policies for the agro-ecological transition by assessing the current biophysical and regulatory constraints that may confront the EU's objective of having 25 % of its agricultural land under OA, which is still far from being achieved (Guyomard et al., 2020).

2. Materials and methods

2.1. Characteristics of organic agriculture in France

With 2.5 million ha in 2020 (i.e. 10 % of France's agricultural area), France is one of the countries in which OA has increased the most (by nearly +13 % since 2019) (Le Douarin, 2021) (Table S2 and S3), which reflects the goal of the French policies to this end since 1997 (Table S4). In 2021, France had 58 413 organic farms, representing 13 % of all farms. France's OA leads Europe in the amount of organic products produced, ahead of Spain, and is second in economic value behind Germany (Le Douarin, 2021). The OA sector has a value of 13 billion euros and maintains a stable percentage of the French food market (6.6 %). Despite sustained growth over the past 10 years, the value of organic products in France fell by 1.3 % in 2021, due to unprecedented inflation and the COVID-19 pandemic, which has forced consumers to make new trade-offs in their purchasing decisions. Furthermore, an oversupply of organic products results in a decrease in their prices (Chatellier, 2024), which explains why farmers seek to adjust supply to meet current demand as closely as possible to maintain attractive farm-gate prices.

2.2. System boundaries

The study focused on N flows associated with all OA production in metropolitan France in 2021, including both crop and livestock production at the farm gate. The system boundaries included all agricultural land area and imported feed in France but excluded food processing, retailing, consumption and export (Fig. 1). We distinguished three main production sub-systems that exchange N flows: cropland, grassland and livestock. N inputs to the system consisted of BNF, atmospheric deposition, manure from conventional agriculture and feed imports from abroad (Table 1). N outputs from the system were primarily through crop and livestock production intended for human consumption (Table 1). No N in any form (e.g. manure) flowed from OA to conventional agriculture. N surplus from the system equalled N inputs minus N outputs.

2.3. Model structure

To analyse the N flows in France's national OA system, we used the existing ALPHA N budget model (Chatzimpiros and Harchaoui, 2023), designed to simulate N flows and cycling in both organic and conventional agri-food systems. Adapting the model originally designed at the global scale, we retained the core equations of the ALPHA model (Chatzimpiros and Harchaoui, 2023) and adapted two equations to build an ALPHA-national model at the national scale (Supplementary Method no. 1). We calibrated input variables of the model using French national agricultural statistics (AgenceBio, 2021) and expert opinion. Specific model modifications included adding N input from OA animal feed from abroad and excluding N input from synthetic fertilisers, which are prohibited in OA, and replacing them with manure from conventional agriculture. Manure sourced from conventional agriculture is authorised in OA in the EU with the exception of manure originating from industrial livestock farms. Each EU member state has defined industrial livestock farming at the national scale (Supplementary Organic regulations). According to specific regulation in France, manure is considered industrial if it comes from monogastric livestock farms with slatted, full-grid or caged floors and exceeds certain animal-density thresholds (Table S1). However, manure from ruminants can be used as a fertiliser in OA in France regardless of the production system. We also excluded compost of green waste (e.g. grass clippings) and annual changes in soil N stocks. In addition, we assumed that human excreta and bio-waste compost included in the ALPHA model were not used for agricultural production because they are prohibited or restricted (Supplementary Organic regulations for bio-waste compost) in OA, respectively. The N schematic flows of the ALPHA national model was presented in Fig. 1

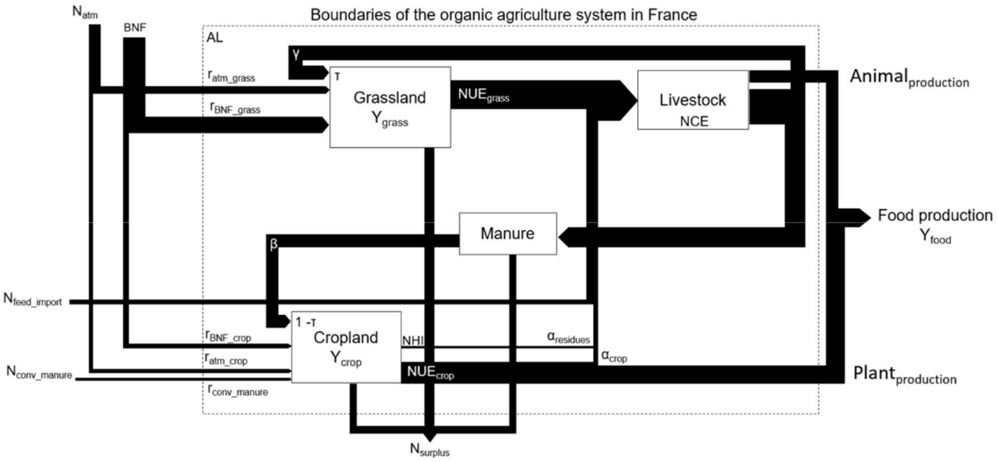

Fig. 1. Diagram of the nitrogen flows represented in the ALPHA-national model, adapted from Chatzimpiros and Harchaoui (2023). See Table 1 for definitions of the variables and units.

Table 1
The 22 model variables by category (Cat.) and their abbreviations (abbrev.), type ((I)nput or (O)utput), values, units and sources.
N: nitrogen, NUE: N-use efficiency.

Cat.	Variable	Abbrev.	Type	Value	Unit	Sources
Food yield ($n = 6$)	Crop yield	Y_{crop}	I	53.6	kg N ha^{-1} yr^{-1} of cropland	Agreste (2020a) Agreste (2023)
	Grass yield	Y_{grass}	O	44.3	kg N ha^{-1} yr^{-1} of grassland	–
	Livestock N-conversion efficiency	NCE	I	14	%	Garnier et al. (2023) Puech and Stark (2023) Rouillé et al. (2023)
	Percentage of crop residues used for feed	$\alpha_{residues}$	I	30	%	Chatzimpiros and Harchaoui (2023)
	Percentage of grassland	τ	I	67.5	%	AgenceBio (2021) Data.gov (2021)
	Percentage of crop production used for feed	α_{crop}	I	24	%	FranceAgriMer (2023)
N cycling ($n = 9$)	Atmospheric deposition rate in cropland	r_{atm_crop}	I	12	kg N ha^{-1} yr^{-1} of cropland	Einarsson et al. (2021)
	Atmospheric deposition rate in grassland	r_{atm_grass}	I	12	kg N ha$^{-1\ \mathrm{yr}^{-1}}$ of grassland	Einarsson et al. (2021)
	Biological N fixation rate in cropland	r_{BNF_crop}	I	19	kg N ha$^{-1\ \mathrm{yr}^{-1}}$ of cropland	Lassaletta et al. (2014)
	Biological N fixation rate in grassland	r_{BNF_grass}	I	25	kg N ha$^{-1\ \mathrm{yr}^{-1}}$ of grassland	Lassaletta et al. (2014)
	NUE in cropland	NUE_{crop}	I	65	%	Billen et al. (2021)
	NUE in grassland	NUE_{grass}	I	75	%	Chatzimpiros and Harchaoui (2023)
	N harvest index of crops	NHI	I	70	%	Chatzimpiros and Harchaoui (2023)
	Percentage of N excreted on grassland	γ	I	58	%	Expert opinion (Chamber of Agriculture and ITAB)
	Percentage of manure N recovered for cropland	β	I	63	%	Expert opinion (Chamber of Agriculture and ITAB) CORPEN (2004) CORPEN (2006) Giovanni (2008) IDELE (2015)
N dependence ($n = 2$)	N in conventional manure	r_{conv_manure}	O	11	kg N ha$^{-1\ \mathrm{yr}^{-1}}$ of cropland	–
	N in imported feed	Nimport_feed	I	12	kt N yr^{-1}	EC (2023)
System-wide ($n = 5$)	Food yield	Y_{food}	O	19	kg N ha$^{-1\ \mathrm{yr}^{-1}}$ of total agric. area	–
	Total agricultural land	AL	I	2253 517	ha	AgenceBio (2021) Data.gov (2021)
	Percentage of animal-based food	Animal$_{production}$	O	30	%	–
	N surplus rate	$N_{surplus}$	O	25	kg N ha$^{-1\ \mathrm{yr}^{-1}}$ of total agric. area	–
	Total NUE	NUE_{tot}	O	43	%	–

and all model input and output variables were described in Table 1 with abbreviations, units, values and sources. The sensitivity of the model outputs to model inputs was assessed using a Morris sensitivity analysis by varying six input variables one-at-a-time by ±10 % (Hamby, 1994). We assessed organic food production and the N cycle in France for 2021.

2.3.1. *Cropland, grassland and livestock production data*

2.3.1.1. Input variables. The area of agricultural land in OA in 2021 studied in this study (AL) (2.2 million ha) including organic cropland (i.e. cereals, vegetables, oilseeds, and protein crops) and grassland (i.e. permanent, temporary and artificial grasslands, and summer pasture).

Artificial grasslands included clover, lucerne, sainfoin, faba beans, vetch, lupin, fodder beet and peas, used exclusively for animal feed. We excluded the area of secondary permanent crops, such as orchards, vineyards and flowers. AL represents 90 % of the total OA fields declared to the EU as part of its Common Agricultural Policy (Data.gov, 2021) based on recent data (AgenceBio, 2021). The percentage of grassland in the total agricultural area (τ) (67.5 %) was estimated from AL (AgenceBio, 2021; Data.gov, 2021).

Crop yield (Y_{crop}) (53.6 kg N ha^{-1} yr^{-1}) was calculated from the overall mean yield of each crop, weighted by its cultivated area and N content. OA area by crop was obtained from national statistics (Data.gov (2021), based on recent data (AgenceBio, 2021). Yield data for wheat, barley, triticale, sunflower, soya bean and maize (t ha^{-1} yr^{-1}), were obtained from a recent study (Agreste, 2023) that estimated a 38–41 % difference in yield between organic and conventional crops at the national scale. For other crops, we used conventional yield data (Agreste, 2020a) and then we referred to the study of Seufert and Ramankutty (2017), which reported a mean difference in yield of 20 % between organic and conventional crops. The N content of each crop was obtained from Lassaletta et al. (2014), although these data were not specific to OA.

Total feed of OA livestock (N_{feed}, kt N yr^{-1}) included feed from grassland (N_{feed_grass}), crops (N_{feed_crop}), crop residues ($N_{feed\_residues}$) and imports from abroad (N_{feed_import}). The weighted national mean percentage of crop production used for animal feed (α_{crop}) (24 %) was based on a recent study (FranceAgriMer, 2023) that estimated this percentage in OA at 42 % in mass equivalent for wheat, maize, barley and triticale. For other crops (i.e. oats, sorghum and sunflower), we used the same percentage (42 %) and for soya bean we assumed 5 %. Variable α_{crop} was used to calculate N_{feed_crop} (kt N yr^{-1}) for animals. The percentage of crop residues used for animal feed ($\alpha_{residues}$) (30 %) was calculated from crop production using an N harvest index (NHI) (70 %) and used to calculate $N_{feed\_residues}$ (kt N yr^{-1}). Values for NHI and $\alpha_{residues}$ came from Chatzimpiros and Harchaoui (2023). N_{feed_import} accounted for the sum of France imports of organic agri-food products intended for animal feed from outside the EU and within the EU. Import trade data from outside the EU were publically available for 2021 (EC, 2023) (Table S5). However, import trade data within the EU were not yet captured by national statistics. These data are difficult to obtain because some feed ingredients are only in transit in several countries. We therefore collected data from Céréopa (Centrer for Study and Research on the Economics and Organisation of Animal Production, pers. comm.) to estimate total imports (EU + non-EU) for France. These data are confidential and based on cross-checks with customs authorities and estimates made by Céréopa based on expert opinion (e.g. brokers, importers) as part of the DURALIM observatory to characterize these flows. N_{feed_import} was estimated at 12 kt N yr^{-1}.

Livestock N conversion efficiency (NCE) (14 %) was calculated as the mean animal-specific NCE weighted by its respective production. We included production of milk, eggs or meat from dairy cows (Interbev, 2021; ProduireBio, 2021), beef cows (Interbev, 2021), veal (Interbev, 2021), dairy ewes (BioRéférences, 2021), meat ewes (Interbev, 2021), dairy goats (ChambreAgriculture, 2017), meat pigs (Interbev, 2021), broiler chickens and laying hens (ChambreAgriculture, 2018). We assumed NCE for ruminants (4 % for meat and 17 % for milk) (Puech and Stark, 2023; Rouillé et al., 2023) and monogastric animals (20 % for meat and eggs) (Garnier et al., 2023) (Tables S6). These calculations yielded a weighted mean NCE of 14 %, which included the feeding requirements of entire breeding and meat production populations.

2.3.1.2. Output variables. Grass yield (Y_{grass}, kg N ha^{-1} yr^{-1}) was calculated as an output of the model based on the equation of Chatzimpiros and Harchaoui (2023), including all N inputs to grassland plus livestock excretion during grazing. N_{feed_grass} (kt N yr^{-1}) was based on the assumption that all grassland production was used to feed livestock.

N_{food_animal} and N_{food_crop} (kt N yr^{-1}) were animal- and crop-based human food, respectively, consumed in France or exported. $Animal_{production}$ and $Plant_{production}$ (%) was the percentage of livestock production and plant production in total production.

2.3.2. Nitrogen cycling

2.3.2.1. Input variables. The mean rate of atmospheric N deposition (12 kg N ha^{-1} yr^{-1}) (Einarsson et al., 2021) was assumed to be the same in cropland (r_{atm_crop}) and grassland (r_{atm_grass}). We multiplied it by the area of each and then summed the products to calculate atmospheric N deposition on AL (N_{atm}, kt N yr^{-1}).

Rates of BNF in cropland (r_{BNF_crop}) (19 kg N ha^{-1} yr^{-1}) were estimated as weighted means using the method of Lassaletta et al. (2014) for each species that could perform BNF (Supplementary Method no. °2 and Table S7). Rates of BNF in grassland (r_{BNF_grass}) (25 kg N ha^{-1} yr^{-1}) were estimated by broking down all different types of grassland. For artificial grassland, we used the same method of Lassaletta et al. (2014) for each species (Table S8). For permanent grassland, temporary grassland and summer pasture, we set the legume cover at 10 %, 30 % and 10 % of the area, respectively (Françoise Vertès, INRAE, pers. comm.) and the BNF of legumes at 150 kg N ha^{-1} yr^{-1} (Chatzimpiros and Harchaoui, 2023). These estimates for the BNF of grasslands (BNF_{grass}, kt N yr^{-1}) are considered as average value for all grasslands in France. Total BNF was calculated as the sum of the BNF of crops (BNF_{crop}, kt N yr^{-1}) and BNF_{grass}.

The percentage of N excreted in grassland (γ) (58 %) was calculated as livestock excretion during grazing divided by total livestock excretion. We estimated the annual grazing time for each species in OA based on expert opinion (Chamber of Agriculture of Pays de la Loire and Technical Institute of Organic Agriculture, pers. comm.). The percentage of manure N recovered from building to fertilise cropland (β) (63 %) was based on the time spent in buildings by each species under French rearing conditions, which had been estimated to calculated N surpluses and stocks in buildings (CORPEN, 2004, 2006; Giovanni, 2008; IDELE, 2015)

The NUE of cropland (NUE_{crop}) (65 %) was set as the weighted mean NUE of cropland based on the study of Billen et al. (2021) for all agriculture in France from 2009 to 2013. The NUE of grassland (NUE_{grass}) (75 %) came from Chatzimpiros and Harchaoui (2023).

2.3.2.2. Output variables. Total N_{conv_manure} (kt N yr^{-1}) was calculated by subtracting BNF_{crop}, N_{atm} and N in organic livestock manure from total crop N fertilisation requirements (Supplementary Method no. °3). The rate of conventional livestock N manure import (r_{conv_manure}, kg N ha^{-1} yr^{-1}) was calculated by dividing N_{conv_manure} by the total N in the manure used.

Total N input (N_{input}, kg N ha^{-1} yr^{-1}) was the sum of BNF_{crop}, BNF_{grass}, N_{atm}, N_{feed_import} and N_{conv_manure} divided by AL. Total N output (N_{output}, kg N ha^{-1} yr^{-1}) was the sum of N_{food_animal} and N_{food_crop} divided by AL and corresponded to the total food yield (Y_{food}) from OA. Total NUE (NUE_{tot},%) was the system's total NUE. N surpluses ($N_{surplus}$, kg N ha^{-1} yr^{-1}) equalled N inputs minus N outputs.

N self-sufficiency ($N_{self\_sufficiency}$,%) equalled the natural N inputs (i.e. BNF and N_{atm}), divided N_{input} (Harchaoui and Chatzimpiros, 2019). N feed self-sufficiency ($N_{feed\_self\_sufficiency}$,%) equalled animal feed N produced in France divided by the total animal N feed requirement.

2.4. Nitrogen indicators

As the aim of this study was to characterise N flows in OA at the national scale, we used the indicators N_{input}, N_{output}, $N_{surplus}$, NUE_{tot}, and $N_{self\_sufficiency}$ and $N_{feed\_self\_sufficiency}$ as efficiency indicators (Table 2). We selected them to summarise the performance of the OA system through its self-sufficiency and ability to minimise soil nutrient surpluses, as

Table 2

Definitions and equations of nitrogen (N) indicators for organic agriculture. Calculated at the scale of France, which was modelled as a single large organic farm. See Table 1 for definitions of the variables.

Indicator	Calculation	Equation	Unit
N_{input}	Sum of N inputs	$N_{input} = \frac{(BNF + N_{atm} + N_{feed\_import} + N_{conv\_manure})}{AL}$	kg N ha^{-1} yr^{-1}
N_{output}	Sum of N outputs	$N_{output} = \frac{(N_{food\_animal} + N_{food\_crop})}{AL}$	kg N ha^{-1} yr^{-1}
$N_{surplus}$	N input minus N output	$N_{surplus} = N_{input} - N_{output}$	kg N ha^{-1} yr^{-1}
NUE_{tot}	N output divided by N input	$NUE = \frac{N_{output}}{N_{input}} \times 100$	%
$N_{self\ sufficiency}$	Natural N inputs divided by total N input	$N_{self\_sufficiency} = \left(\frac{BNF + N_{atm}}{AL}\right)/N_{input} \times 100$	%
$N_{feed\ self\ sufficiency}$	N feed produced in France divided by animal N feed requirement	$N_{feed\_self\_sufficiency} = \left(\frac{N_{feed\_grass} + N_{feed\_crop} + N_{feed\_residues}}{N_{feed}}\right) \times 100$	%

outlined by the European Union Green Deal (EC, 2020).

3. Results

3.1. Nitrogen flows in organic agriculture in France in 2021

In 2021, OA in France covered 10 % of agricultural land (AgenceBio, 2022b), with the percentage of organic livestock in total livestock ranging from 2 % for sows to 18 % for laying hens (Agreste, 2020b). A simplified diagram of N flows in French OA distinguished internal and external N flows (Fig. 2). Total N input for OA in France was estimated at 44 kg N ha^{-1} yr^{-1} (Table 3).

The main N input sources were BNF (53 %), followed by atmospheric deposition (27 %), imported feed (12 %) and conventional manure (8 %). Of these total N inputs, 19 kg N ha^{-1} yr^{-1} became food, and 25 kg N ha^{-1} yr^{-1} was either lost to the environment or remained in soil N stocks. N surpluses from cropland and grassland were 29 and 15 kg N ha^{-1} yr^{-1}, respectively. Overall, the estimated NUE_{tot} for OA in France was 43 %, due to the percentage of animal production in total production (30 %) and the sub-system's NUE or NCE, which were much lower for the livestock NCE (14 %) than for the NUE of cropland or grassland (65 % and 75 %, respectively).

Grassland provided nearly all of the feed for ruminants (90 % of total N in feed) and 73 % of the BNF input to the system. BNF was slightly higher for grassland than for cropland (25 and 19 kg N ha^{-1} yr^{-1}, respectively) because the former contained forage legumes that fixed large amounts of N and cropland contained protein crops (12 % of cropland area) that also fixed N. The main N outputs were crop-based food (70 %), followed by animal-based food (30 %) (Fig. 2). Of the total crop production, 76 % was used for human food and 24 % for animal feed. Of the latter, 14 % became animal-based food and 86 % was excreted.

Table 3

Nitrogen (N) indicators for organic agriculture in France in 2021. See Table 2 for definitions of the indicators.

Indicator	Value
N_{input}	44 kg N ha^{-1} yr^{-1}
N_{output}	19 kg N ha^{-1} yr^{-1}
$N_{surplus}$	25 kg N ha^{-1} yr^{-1}
NUE_{tot}	43 %
$N_{self\text{-}suffiency}$	80 %
$N_{feed\ self\ sufficiency}$	87 %

French OA was 80 % self-sufficient in N (Table 3). The remaining 20 % of external inputs came from imported feed (12 %) and conventional manure (8 %) (Fig. 2). Of the total N excreted by livestock, 58 % was excreted during grazing and 42 % in buildings. More than 60 % of the excretion in buildings was used to fertilise crops, while the rest was lost in buildings (Fig. 2). This surplus explained the import of 11 kg N ha^{-1} yr^{-1} of manure from conventional agriculture to meet the N requirements of OA crops. The organic manure use to fertilise OA crops came mainly from ruminants (72 %), followed by monogastric animals (28 %).The estimated N feed self-sufficiency was high (87 %) (Table 3) due to the capacity of permanent, temporary and artificial grasslands, and summer pasture to feed ruminants. Excluding these sources of feed, the feed self-sufficiency of cropland for animals was only 55 % (Fig. 2).

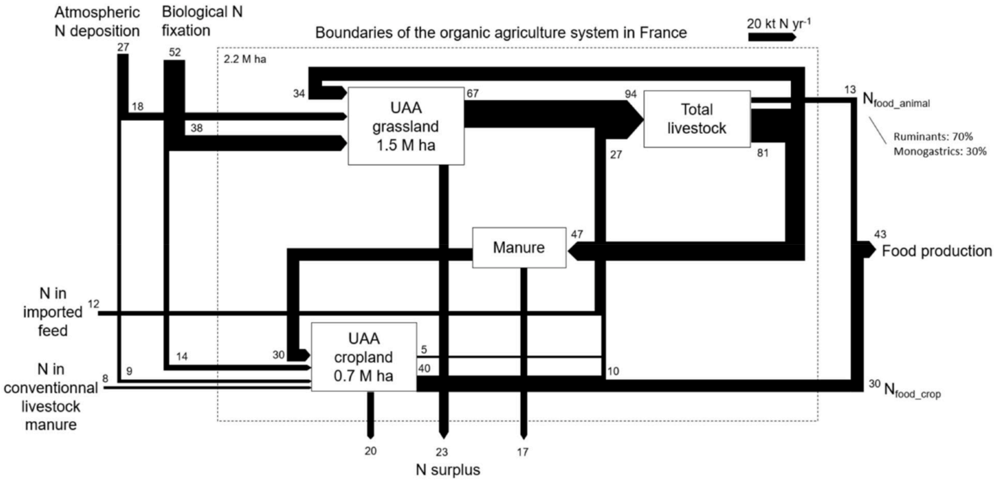

Fig. 2. Diagram of nitrogen (N) flows (kt N yr^{-1}) in organic agriculture in France in 2021. France was modelled as a single organic farm composed of three sub-systems that exchange N flows: cropland (i.e. cereals, vegetables, oilseeds and protein crops), grassland (i.e. permanent, temporary, and artificial grasslands, and summer pasture) and livestock. The width of the arrow is proportional to the size of flow.

3.2. Nitrogen production of organic agriculture in France

Grassland covered much more AL (67 %) and produced much more N (67 kt N yr^{-1}) than cropland did (33 % and 40 kt N yr^{-1}, respectively) (Figs. 2 and 3a). The area used to produce vegetables, oilseeds, and protein crops covered 11 % of AL and produced a lower percentage of the system's total N production (10 %) than cereals or grassland did (Fig. 3b). Wheat and maize account for 49 % and 11 % of N production from cereals respectively.

Notably, 63 % of N production of AL came from permanent, temporary and artificial grasslands, and summer pasture (Fig. 3b), which were found in the dairy and beef systems (Fig. 3c), which together represented 60 % of total N production from animal products, followed by chickens and eggs (25 %).

3.3. Sensitivity analysis

The sensitivity analysis indicated that model output indicators were most sensitive to NUE_{crop}, NUE_{grass} and r_{BNF_grass} and least sensitive to NCE, β and α_{crop} (Fig. S1 and Table S9). The N indicators varied from -6 % to +7 % for the former and from -3 % to +4 % for the latter for a -10 or +10 % change in each input variable, respectively.

With limited N availability in organic systems, NUE_{crop} was an influential variable that impacted total N fertilisation for cropland. When NUE_{crop} increased (+10 %), less N input was needed (−6 %) from conventional manure to fertilise crops, which increased NUE_{tot} and N self-sufficiency (+6 %) but did not influence N feed self-sufficiency (Fig. S1a). To a lesser extent, when NUE_{grass} increased (+10 %), grasslands were more productive, which influenced NUE_{tot} (+4 %), N self-sufficiency (+2 %) and N feed self-sufficiency (+1 %) (Fig. S1b). Similarly, when the rate of BNF in grassland (r_{BNF_grass}) increased (+10 %), grasslands produced more N, so animals ate and excreted more, which required less conventional manure and increased the system's N self-sufficiency (+2 %), thus decreasing the import of conventional manure in OA (Fig. S1d). The challenge in estimating r_{BNF_grass} is that it requires accurately estimating both the percentage of legumes in grassland and the rate of BNF of individual legume species (Einarsson et al., 2021).

4. Discussion

4.1. Limitations of the study

The study had three main limitations. The first limitation was the

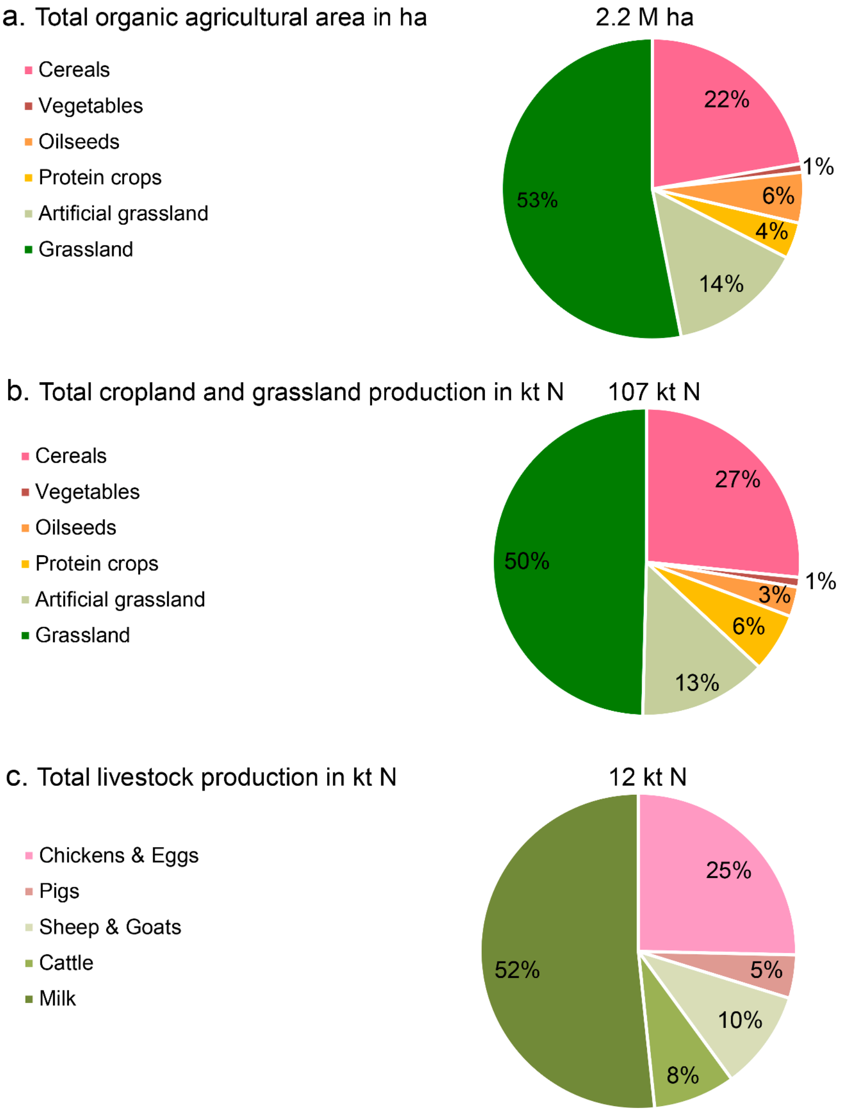

Fig. 3. Distribution of organic agricultural land and associated nitrogen (N) production in France in 2021. (a) distribution of the area of types of cropland and grassland under organic agriculture in 2021 (AgenceBio, 2021) and composition of N production from types of (b) cropland and grassland or (c) livestock.

constraint to perform the analysis on single year data (2021). Although annual crop and livestock productivity data on OA were unavailable, productivity does fluctuate and could probably change the N balance. For instance, the average organic wheat yield in France for 2021 was 15 % higher than the average of the preceding four years (AgenceBio, 2024; Agreste, 2024). However, a recent analysis indicated a relatively stable annual yield gap between organic and conventional crops across consecutive years (Agreste, 2023).

The second limitation was the exclusion of annual changes in soil N stocks at the national scale. Measuring soil N stocks could improve this type of modelling (Kautsar et al., 2019).

The third limitation was the lack of data on N efficiency in OA to calibrate the model. NUE_{crop} is an uncertain variable in OA, and it determines the amount of conventional manure required. Recent studies have shown uncertainty in NUE_{crop} in France, as NUE_{crop} varies greatly and depends on fertilisation; thus, it is difficult to average for an entire country. According to FAOSTAT (2023a), NUE_{crop} in France was 54 % based on the previous 5 years of published data (2017–2021). Einarsson et al. (2021) estimated NUE_{crop} as 70 % based on 2015–2019 data, using a larger cropland boundary that included temporary grassland. Zhang et al. (2021) analysed NUE_{crop} to estimate the uncertainty in national N budgets. They found that for France from 2011 to 2015 excluding the estimate of Billen et al. (2021) (65 %) that we chose, NUE_{crop} ranged from 43 to 74 %. These values were derived from estimated N budgets for crop production from 10 studies from 1961 to 2015 (Zhang et al., 2021). Furthermore, the difference in NUE_{crop} between OA and conventional agriculture remains uncertain. We assumed that NUE_{crop} in OA was equivalent to that of all cropland in France, as estimated by Billen et al. (2021). For instance, at the farm scale in Germany, a recent study estimated that the NUE of an organic arable farming system (83 %) was higher than that of a conventional arable farming system (77 %) (Chmelíková et al., 2021). In the present study, NUE_{crop} was set at 65 % for OA, which may have decreased crop N requirements and the need for conventional manure in OA. To eliminate dependence on conventional manure, we estimate that the NUE_{crop} of OA should increase to 75 %.

4.2. Comparison of nitrogen flows between organic agriculture and other agricultural systems

There is no national study of N flows in OA. However, it is interesting to compare the characteristics of OA flows obtained with other systems studied at national or European scale. We compared results of the present study to those for all agriculture in France in 2013 and 1882 (Harchaoui, 2019) (Table 4). As OA covered only 3 % of the agricultural land in 2013 (FiBL, 2023), French agriculture was essentially conventional. The percentage of BNF in total N input in OA was 37 percentage points higher than that in conventional agriculture because OA cropping systems always have more N-fixing crops, which are needed to increase N inputs to maintain crop yields (Barbieri et al., 2023). For the outputs, OA had lower yields (by 34 kg N ha^{-1} yr^{-1}) than conventional agriculture due to its lower productivity (Alvarez, 2022). Our estimate of N surplus (25 kg N ha^{-1} yr^{-1}) at the national scale was in line with the recent mean estimate for 71 organic farms in Europe (28 kg N ha^{-1} yr^{-1}) (Reimer et al., 2023). In addition, OA had lower N surplus per ha (by 23 kg N ha^{-1} yr^{-1}) than conventional agriculture in France (Table 4), which agrees with a previous comparative analysis of N surplus in organic and conventional agriculture (Kelm et al., 2008). Although the areas under OA and conventional agriculture are different, our results seem to indicate that the 50 % reduction in nutrient surpluses envisaged by the European Union's Green Deal (EC, 2020) is achievable with OA in regard to N. The NUE_{tot} of OA was 10 % points lower than that of conventional agriculture because the former is less productive due to a lower animal NCE and higher percentage of animal production in the total production (by 13 percentage points). The 1882 data were more uncertain, but they made it possible to compare OA indicators to those of agriculture without synthetic fertilisers. The 1882 data indicated lower total N input (by 28 kg N ha^{-1} yr^{-1}), lower N surpluses (by 24 kg N ha^{-1} yr^{-1} and no feed imports. The present study of OA in France highlighted three key sustainability characteristics. First, because synthetic N fertiliser is prohibited, OA relies necessitates on BNF as the primary N input and thus depends less on fossil fuels than to conventional agriculture (Chatzimpiros and Harchaoui, 2023). Second, with N surplus as a key indicator of sustainable farming systems (van Grinsven et al., 2012), OA has lower N surplus than conventional agriculture at the national scale. Third, the products produced by OA are more closely aligned with the percentages of animal (30 %) and plant (70 %) products recommended in a healthy diet (Springmann et al., 2018) than those produced by conventional agriculture. This percentage differs greatly from current N food consumption in France, which heavily favours consumption of animal products (62 %) (Billen et al., 2018). However, compared to conventional agriculture, OA in France is less productive per ha on average and equally dependent on feed imports from abroad. This raises concerns about the vulnerability of certain segments of OA livestock production to potential disruption in foreign feed trade (Loi et al., 2024).

Table 4
Indicators of organic agriculture (OA) in 2021 and all agriculture in France in 2013 and 1882. BNF: biological N fixation, N_{atm}: atmospheric N deposition, N_{conv_manure}: N in import of conventional manure, N_{ind}: N synthetic fertilisers, N_{import_feed}: N in imported feed, $N_{surplus}$: N surpluses, NUE_{tot}: total N-use efficiency.

Indicator	OA in France in 2021	Agriculture in France[a]		Unit
		2013	1882	
N_{input}	44	101	16	kg N ha^{-1} yr^{-1}
BNF	*53*	*16*	*69*	% of N_{input}
N_{atm}	*27*	*5*	*31*	% of N_{input}
N_{conv_manure}	*8*	*0*	*0*	% of N_{input}
N_{ind}	*0*	*69*	*0*	% of N_{input}
N_{import_feed}	*12*	*10*	*0*	% of N_{input}
N_{output}	19	53	15	kg N ha^{-1} yr^{-1}
$N_{surplus}$	25	48	1	kg N ha^{-1} yr^{-1}
NUE_{tot}	43	53	95	%
$Animal_{production}$	*30*	*17*	*12*	% of N_{output}
$Plant_{production}$	*70*	*83*	*88*	% of N_{output}

[a] Adapted from Harchaoui and Chatzimpiros (2019).

The 100 % agro-ecological scenario for Europe of Billen et al. (2021) showed similarities with the current N flows observed in OA in France. Note that Billen et al. (2021) assumed a large percentage of recycling of human excreta as a source of N, a practice that were not prevalent in our case study. However, the estimated livestock NCE in OA (14 %) was similar to that of the agro-ecological scenario (13 %) (Billen et al. (2021). The percentage of ruminant and monogastric animal products in livestock production in OA was 70 % and 30 %, respectively, and was similar to that of the agro-ecological scenario (Billen et al. (2021). The percentage of animal products in total food production in OA (30 %) was also consistent with that in the 100 % agro-ecological scenario (25 %, excluding fish) (Billen et al., 2021). Furthermore, using data from the French food balance sheet (FAOSTAT, 2023b), we estimated that only 9 % of the total N human diet in France was organic (Table S10). The percentage of organic products in the consumer market is 6 % (AgenceBio, 2022a).

4.3. Dependence of organic agriculture on external nitrogen sources

OA depended on external N resources. The import of animal feed and conventional manure represented 20 % of the total N input in OA (Table 4), which agrees with the 24 % (with 16 % of conventional manure) estimated by a recent farm-wide assessment of OA across Europe (Reimer et al., 2023) and the 23 % (including conventional manure, forage and straw) estimated by a study of organic farms in three agricultural districts in France (Nowak et al., 2013b).

In the present study, ca. 20 % of the manure used to fertilise organic cropland came from conventional agriculture (i.e. 11 kg N ha^{-1} yr^{-1} of cropland). In a study of Danish organic farms in 2011, ca. 24 kg N ha^{-1} yr^{-1} of N inputs to organic crops via manure came from conventional agriculture (Oelofse et al., 2013). The present study estimated lower dependence because it excluded imports of litter from conventional agriculture, which is authorised in OA and because of NUE_{crop}. Overall, these results illustrate a general concern in Europe about the dependence of OA on conventional agriculture. Furthermore, there exist various degrees of strictness in defining industrial livestock manure authorised in OA across different EU countries (Table S1) with most regulations being more stringent than those in France. This suggests a potential trend towards stricter regulations in France, aiming to remove all connections between OA and conventional agriculture (Regulation (EU) (2018/848)), and align more closely the principles of agro-ecology (Nowak et al., 2013b; Løes et al., 2016) (Supplementary Organic regulations for inspection methods). For instance, Austrian regulations authorise up to 25 kg N ha^{-1} $yr^{-1}$of manure from conventional agriculture (Løes et al., 2016), while Danish regulations authorise up to 70 kg N ha^{-1} yr^{-1}, however, Denmark has decided to prohibit the use of conventional manure and straw in OA by 2022, and subsequently moderated this decision due to the limited availability of acceptable alternatives, favouring a more gradual approach (Oelofse et al., 2013). Reducing this dependence on conventional manure could involve extending the time that OA livestock currently spend in confinement. Doing so would increase the amount of organic manure recovered for fertilising cropland, thus increasing the supply of N. However this proposed change conflicts with social acceptability, as highlighted by Delanoue and Roguet (2015) and raises concerns about animal welfare in OA. Thus intensifying livestock confinement in buildings is not considered a viable solution. In addition, more livestock to produce more manure is a solution, but not in line with livestock trends and would require importing more organic feed, often from outside the EU, which would decrease the circularity and efficiency of N use in OA.

Of all crops (except forage crops) fed to animals, 45 % was imported (Fig. 2). Imported feed ingredients consisted mainly of soya bean grain and meal (Table S5) and were used mainly to feed monogastric animals (37 % of total feed N), followed by ruminants (6 %). In a recent comprehensive two-year survey, organic feed manufacturers in France produced specifically for laying hens, which represented ca. 66 % of the use of feed ingredients in France (Canale et al., 2021). Nevertheless, soya bean area in France has increased by a factor of ca. 50 since 2001, but remains relatively small (47,680 ha) (Data.gov, 2021), which means that France cannot be self-sufficient in both organic and conventional soya beans and continues to import increasing amount of animal feed (Table S11). Feed manufacturers in France must import soya bean meal mainly from Africa, India, China, the Americas and elsewhere in Europe (Canale et al., 2021; EC, 2023), to meet OA needs. We argue that OA faces similar criticisms as conventional agriculture (Lassaletta et al., 2013) regarding its dependence on imported feed. To maintain a sufficient of N resources to OA, especially when maintaining or increasing livestock numbers, it's imperative to consider strategies for sourcing at the national or European scale. However, this approach may raise additional trade-off between OA food production and land-use considerations.

However, decreasing the number of livestock to match the feed production in France may change land use. A decrease in the number of livestock in OA could equate to a lack of manure for fertilising cropland and a decrease in grassland area. However, some BNF from legumes in grassland can also be transferred to cropland by maintaining grassland without animals, as semi-natural areas. One method involves incorporating legumes and temporary grass into crop rotations (Barbieri et al., 2019), which is used particularly in some vegetable farms, or cutting grass to bury legumes in the soil before planting cereals. Another approach is based on anaerobic biogas plants, in which grass is cut and used as a feedstock to generate energy, with the resulting digestate used as fertiliser for cropland. Both of these strategies should warrant further investigation through a comprehensive environmental assessment. Additionally, a promising solution for N resources involves large-scale recycling of household bio-waste into organic fertiliser for OA (AND-International, 2022), which has demonstrated significant potential to supply N (Oelofse et al., 2013). However, household bio-waste, as outlined in Annex II Regulation (EU) (2018/848) in OA, is the only organic soil fertiliser subject to quality requirements. It must originate from a closed system and be collected by local authorities for use in OA, which currently limits its use (Supplementary Organic regulations for bio-waste compost). In addition, household bio-waste is not well accepted by organic farmers (Case et al., 2017) due to its concentrations of heavy metals (i.e. zinc, lead, cadmium, nickel and copper) (Gottschall et al., 2023).

5. Conclusions

This nitrogen flows assessment study conducted in organic agriculture in France reveals that nitrogen availability is limited. The study demonstrated the sustainability of organic agriculture from a nitrogen perspective, characterized by a nitrogen surplus per ha that is 50 % lower than conventional agriculture at the national scale. It also showed an adequate balance between animal and vegetal production in alignment with healthy dietary recommendations. In contrast, the study also pointed out a potential vulnerability of this organic farming system due to its dependence on external nitrogen resources from conventional agriculture and feed imports. This highlights the role of livestock as a nitrogen resource to support organic agriculture's development, but also the simultaneous risk of increasing dependence on feed imports, which runs counter to the nitrogen self-sufficiency and sustainable system advocated by the Green Deal policy. Several solutions have been identified to address these challenges, such as incorporating more legumes in rotations to fix biological nitrogen, and maintain livestock to maintain a supply of nitrogen resources. These measure are essential to achieve the goal of having 25 % of the European Union's agricultural land under organic agriculture while ensuring nitrogen self-sufficiency. The sensitivity analysis underscores the necessity for enhanced data on organic agriculture within national statistics, mirroring the comprehensive data available for conventional agriculture. This initial analysis provides a first quantification of all nitrogen flows at the national scale that can serve as a basis for comparison with other countries in Europe. Additionally, an existing nitrogen budget model has been adapted to assess potential for expanding organic agriculture. Data collection and modelling approaches can also be adapted to examine phosphorus flows, which pose another major challenge for organic agriculture in the long term, or can also be fine-tuned at a smaller scale (e.g. a European administrative region). Beyond the interest of public authorities, the decline in public demand for organic products, combined with the challenges of nutrient availability in organic agriculture, could threaten the future of organic agriculture.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Fanny Vergely: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aurélie Wilfart:** Writing – review & editing, Validation, Supervision. **Joël Aubin:** Writing – review & editing, Validation, Supervision. **Souhil Harchaoui:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

Data will be made available on request.

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Supplementary materials

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