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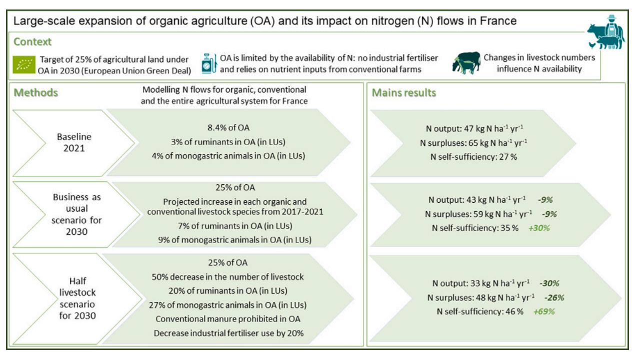
HIGHLIGHTS

- N flows were modelled for organic, conventional and the entire agricultural system.
- Two distinct pathways for organic and conventional livestock were modelled.
- Increasing organic livestock decreased productivity of the agricultural system.
- Decreasing livestock numbers implies trade-offs that impact crop yields and efficiency.
- 25 % of organic agriculture requires decreasing consumption of animal products.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Organic agriculture (OA) is promoted in the European Union (EU) as a sustainable form of agriculture. However, its expansion may be limited by its dependence on external nitrogen (N) resources, such as conventional manure and imported feed, as it prohibits the use of industrial fertilisers. There is currently no consensus on the role of livestock in scenarios of OA expansion, despite their critical contribution to increasing soil fertility through grazing and nutrient cycling via manure and urine.

Abbreviations: ALPHA, Agricultural Limits quantification through PHysical flows Analysis in cropland, grassland and livestock compartments; BAU, business as usual; BNF, biological nitrogen fixation; EU, European Union; GHG, green-house gas; HL, half livestock; LUs, livestock units; N, nitrogen; N_{atm}, atmospheric nitrogen deposition; NCE, nitrogen conversion efficiency; N_{food_animal}, animal-based human food consumed in France or exported; N_{food_crop}, crop-based human food consumed in France or exported; N_{import_feed}, feed imports from abroad; N_{ind}, industrial nitrogen fertilisers; N_{input}, sum of atmospheric nitrogen deposition, biological nitrogen fixation, industrial nitrogen fertiliser and feed imports; N_{manure}, total livestock nitrogen excretion; N_{manure_avail}, manure nitrogen available for cropland application; N_{manure_crop}, manure nitrogen used to fertilise cropland; N_{manure_grass}, livestock nitrogen excretion during grazing; N_{output}, total nitrogen contained in animal and crop agricultural products; $N_{self\_sufficiency}$, natural nitrogen inputs (i.e. atmospheric nitrogen deposition and biological nitrogen fixation) divided by nitrogen inputs; $N_{surplus}$, nitrogen inputs minus nitrogen outputs; NUE, nitrogen-use efficiency; NUE_{crop}, nitrogen-use efficiency of cropland; NUE_{grass}, nitrogen-use efficiency of grassland; OA, organic agriculture; P, phosphorus; UAA, utilised agricultural area; Y_{crop}, cropland yield; Y_{food}, total food yield; Y_{grass}, grassland yield; α_{crop}, percentage of crop production used for animal feed; $\alpha_{residues}$, percentage of crop residues used for animal feed; β, percentage of manure nitrogen recovered from barns to fertilise cropland; γ, percentage of nitrogen excreted in grassland; τ, percentage of grassland in the total utilised agricultural area.

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OBJECTIVE: Here, we explored the expansion of OA with a view to having 25 % of total agricultural land under OA by 2030, as defined by the EU Green Deal policy, using two development pathways for organic and conventional livestock: business as usual (BAU) and halving the number of livestock (HL).
METHODS: We modelled N flows for organic, conventional and the entire agricultural system using an existing N budget model applied at the national scale for France.
RESULTS AND CONCLUSIONS: The results indicated that changing the numbers of livestock species when expanding OA influences N availability. Transitioning to 25 % of agricultural land under OA along with increasing the number of organic livestock in the BAU and HL scenarios decreased total N input, especially industrial fertiliser and feed imports, by 9 % and 28 %, respectively, while decreasing N surpluses by 9 % and 26 %, respectively. In parallel, in the BAU and HL scenarios, biological N fixation increased by 32 % and 61 %, respectively, N output in animal and crop products decreased by 9 % and 30 %, respectively, due to the lower productivity of organic livestock and crops. Notably, this transition implied decreasing human consumption of animal products in the BAU and HL scenarios by 5 % and 30 %, respectively. The scenarios demonstrated the key contribution of livestock and biological N fixation of legumes to the expansion of OA, but further analysis is required, such as considering changes in human diets, farming practices or land use.
SIGNIFICANCE: This study highlights simultaneous trade-offs of two agricultural systems at the national scale.

1. Introduction

Sustainable food systems must ensure sufficient, adequate and healthy food for all populations, while simultaneously addressing the multifaceted challenges of adapting to climate change (Abbass et al., 2022), erosion of biodiversity (Guerra et al., 2020) and disturbances of nutrient cycles (Drinkwater and Snapp, 2007). Transitioning from conventional (i.e., non-organic) agricultural systems that depend on non-renewable resources to organic agricultural systems is viewed as one strategy to address these challenges (Barbieri et al., 2021). The European Union (EU) action plan for organic agriculture (OA) (2021/2239 (INI)), as part of its "Green Deal" policy, works to move towards a sustainable food system. Its aims are to decrease nutrient surpluses by at least 50 %, decrease industrial fertiliser use by at least 20 % and have at least 25 % of the EU's agricultural land under OA by 2030. However, agriculture is limited by nitrogen (N) availability, conventional agriculture can use industrial fertilisers compared to OA (Berry et al., 2002; Connor, 2008), which can restrict its expansion (Muller et al., 2017; Barbieri et al., 2021; Billen et al., 2021).

In OA, the N supply can be accomplished by extending crop rotations to include legumes, which can perform biological N fixation (BNF) (Mäder et al., 2002; Barbieri et al., 2023) or involves recycling N flows from legumes in grassland through livestock (Berry et al., 2002; Peyraud et al., 2012; Dumont et al., 2016). Livestock contribute to soil fertility through the physical effects of grazing and the return of nutrients in manure and urine to the soil, a highly valued service in organic systems, which compensates for the prohibition of industrial fertilisers (Watson et al., 2002). The livestock sector thus appears essential to the N budget of OA. Nevertheless, it seems essential to consider the respective roles of ruminants and monogastric animals, as their environmental performance differs and may be complementary depending on the context and objectives (Peyraud et al., 2019).

Several agri-food scenarios at multiple scales indicated that livestock numbers must decrease greatly to maintain the availability of sustainably produced food (Van Zanten et al., 2018), increase nutrient circularity and decrease green-house gas (GHG) emissions (van Selm et al., 2022) or maintain the agri-food system within environmental limits (Springmann et al., 2018). The review of Borghino et al. (2024) identified 23 modelling studies of expansion of OA at different scales that considered food supply and demand and found an overall mean decrease of 28 % in the number of livestock units (LUs) between the baseline situation and the expansion of OA. Other EU (Agora Agriculture, 2024) and national(Drofenik et al., 2023) scenarios, not included in the review of Borghino et al. (2024), agreed on the need to decrease livestock numbers, but differed in the percentage of decrease. However, apart from the study of Barbieri et al. (2021) at the global scale, no scenario of OA expansion has considered the contribution of livestock as a source of N, in contrast to the scenarios of Muller et al. (2017) and Erb et al. (2016), which forecast a decrease in livestock numbers. The study of Barbieri et al. (2021) included additional sources of N such as conventional manure, which could potentially become prohibited in OA and pose biophysical and regulatory challenges to the future expansion of OA (Beck et al., 2014; Reimer et al., 2023). As the expansion of OA is promoted and faced the increasing pressure to decrease livestock numbers in the agri-food scenarios, it becomes essential to address the question of how changes in organic and conventional livestock numbers influence N availability in OA and the production of food in the agri-food system. To date, few studies have examined the separate impacts of changes in organic and conventional ruminant or monogastric animals in the agri-food system at the national scale. Thus, potential impacts of large-scale OA expansion on organic and conventional livestock production remain unknown.

Several studies have assessed the overall functioning of the agri-food system assuming expansion of OA to up to 25 % of the EU's agricultural land, as recommended in the EU Green Deal policy (Beckman et al., 2020; Billen et al., 2024). However, few distinguish organic and conventional agriculture when assessing the entire agri-food system (Barbieri et al., 2021) that allows to improve understanding of dynamics of N flows and exchanges between the two systems. To date, two studies have used a biophysical model to develop scenarios of the expansion of OA in France (Couturier et al., 2016; Billen et al., 2018). However, one did not specifically assess N flows (Couturier et al., 2016), and the other developed a scenario in which animal products in the human diet in France were halved (Billen et al., 2018). To our knowledge, no published study of OA expansion has simultaneously considered EU Green Deal targets at the national scale, dependence on conventional manure and pressure to decrease livestock number in the agri-food system while distinguishing organic and conventional agriculture.

From 2013 to 2023, the number of cattle and pigs in the EU decreased by 5 % and 6 %, respectively (Eurostat, 2025), while the number of chickens increased by 9 % (FAOSTAT, 2024a). In comparison, the number of organic sheep, goats and cattle has increased (Eurostat, 2024), although the organic livestock sector faces challenges such as disease management, insufficient organic feed and complex certification procedures (Suresh, 2024). Despite being Europe's leading agricultural producer (i.e producing 18 % of the total value of agricultural products in the EU-27) (Agreste, 2024b), France is losing farms every year, which influences all species, as the number and production of the main species (i.e. cattle, pigs and chickens) continually decreasing (Agreste, 2023b, 2023c, 2023f). In 2021, OA covered only 9 % of France's agricultural land, raising questions about the availability of N. More specifically, there is a lack of knowledge regarding the potential expansion of OA in France considering the changes of organic and conventional livestock, as well as the long-term prohibition using conventional manure in OA. We sought to understand consequences of changes in the number of livestock on the environmental and productive performance of the agri-food system by distinguishing organic and conventional agriculture, particularly in relation to large-scale expansion of OA and its impact on N flows. The aim of this study was to explore and discuss trade-offs associated with impacts of current livestock trends up to 2030 if OA is adopted at a large scale, using France as a case study. To address this research gap, we (i) generated the baseline and two development scenarios for organic and conventional livestock at the national scale; (ii) modelled N flows for organic, conventional and the entire agricultural system and (iii) assessed how changes in livestock production influence the functioning of N flows using productivity and efficiency indicators.

2. Materials and methods

2.1. System boundaries

The study examined all agriculture at the national scale, with specific focus on the coexistence of systems operating under the organic label of EU Regulation (2018/848, 2025) (here-after, "OA") and those using conventional (i.e. non organic) practices. The system boundaries included all UAA and imported feed in France, but excluded food processing, retailing, consumption and export (Fig. 1). Three sub-systems were delineated in each production system: cropland, grassland and livestock. Cropland production consisted of cereals, vegetables, oilseeds, protein crops, forages and industrial crops (see Table S2 for details). Grassland production consisted of permanent, temporary and artificial grasslands (Table S2). Animal production consisted of milk, eggs or meat from dairy cattle, beef cattle, dairy ewes, meat ewes, dairy goats, broiler chickens, laying hens and pigs (Table S1). Areas used to grow secondary permanent crops, including orchards, vineyards and flowers were excluded from the analysis. These three sub-systems exchanged N flows (i.e. manure, residues and feed). N inputs to the system consisted of atmospheric N deposition, BNF and feed imports from abroad. We excluded imports of animal- and crop-based human food. For the organic system, we added conventional manure as an N input. N outputs from the system were primarily animal- and crop-based human food. N surplus from the system equalled N inputs minus N outputs.

2.2. Model structure: use of the ALPHA-national model

To analyse N flows in France's national agri-food system, we adapted the previously developed ALPHA N budget model (Chatzimpiros and Harchaoui, 2023), originally designed to simulate N flows and cycling at the global scale. Retaining the core structure and most equations of the original model, we developed the ALPHA-national model to represent national scale N flows (Vergely et al., 2024), with modifications to explicitly represent the coexistence of organic and conventional agricultural systems. Specific model modifications included adding N input from animal feed (organic and conventional) imported from abroad and the transfer of manure from conventional to organic systems (Supplementary Methods no.1). No N in any form flowed from OA to

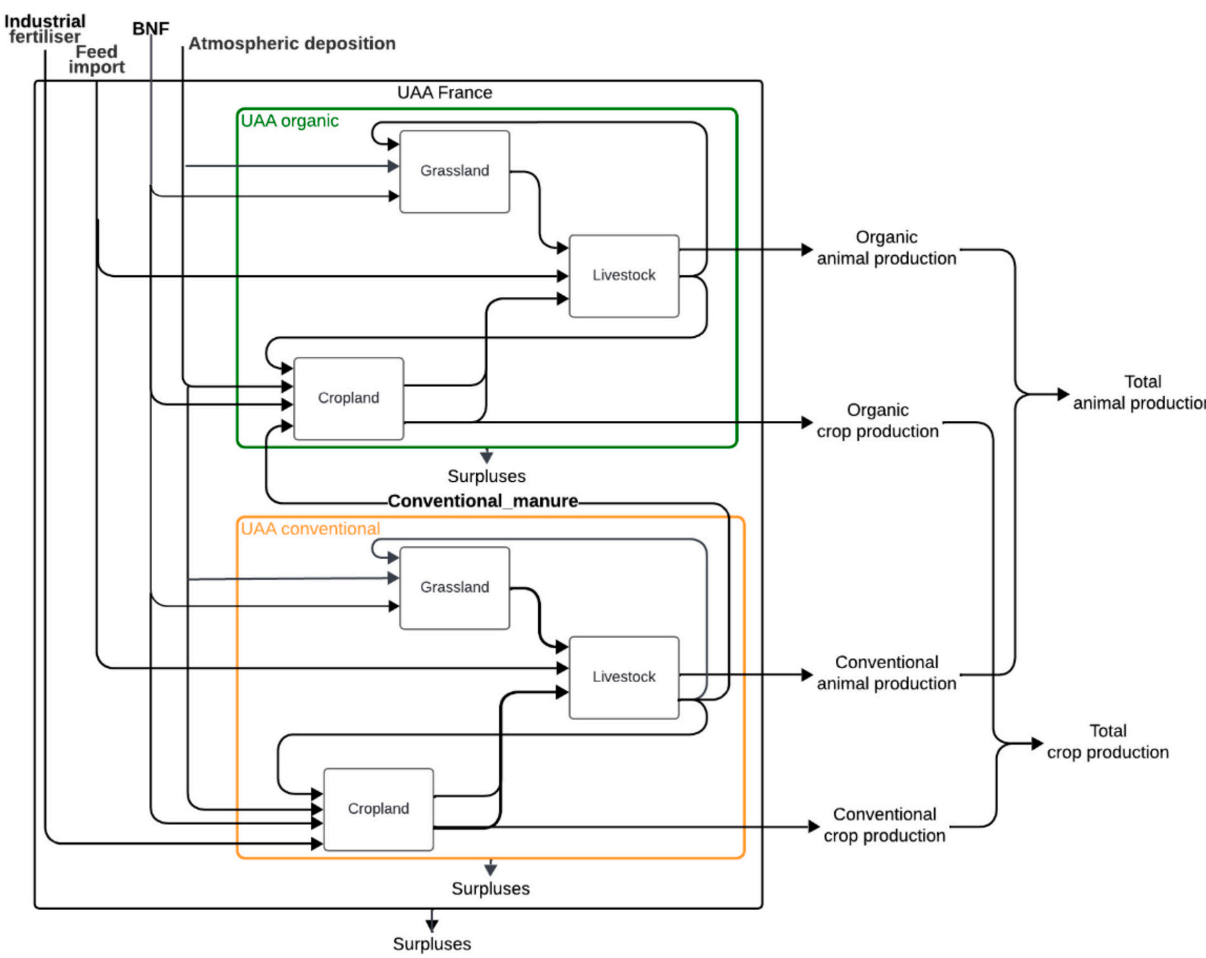

Fig. 1. Nitrogen (N) flows in organic and conventional agriculture represented in the ALPHA-national model. Adapted from Chatzimpiros and Harchaoui (2023) and used by Vergely et al. (2024). France was modelled as two coexisting production models, one organic and the other conventional, connected only by conventional manure used in the organic system. We studied three sub-systems that exchange N flows: cropland production (i.e. cereals, vegetables, oilseeds, protein crops, forages and industrial crops), grassland production (i.e. permanent, temporary and artificial grasslands) and animal production (i.e. milk, eggs or meat from dairy cattle, beef cattle, dairy ewes, meat ewes, dairy goats, broiler chickens, laying hens and pigs). BNF: biological nitrogen fixation, UAA: utilised agricultural area.

conventional agriculture. The resulting ALPHA-national model thus captures interactions and N exchanges between coexisting organic and conventional agricultural systems at the national scale. In addition, we assumed that recycled food waste (i.e. bio-waste compost) and human excreta, included in human waste in the ALPHA model, were not used in OA because they are restricted or prohibited (see the Supplementary Material for organic regulations for bio-waste compost), respectively. We also did not consider human waste in the conventional agricultural system, but we showed that it can be a source of N, and we added industrial fertiliser as an N input. Compost of green waste (e.g. grass clippings) was not considered in the ALPHA model.

Calibration of the organic agricultural system in France for 2021 was adapted from the approach developed by Vergely et al. (2024), with modifications to the allocation of cropland and grassland areas (i.e. a new "forage" category created in crops instead of in "artificial grassland") (see Table S3 for details). We calibrated the model for the year 2021. Because we excluded the organic area of secondary permanent crops, the organic UAA represented 90 % of the total OA fields declared to the EU as part of its Common Agricultural Policy (Data.gov, 2021) based on data from Agence Bio (i.e. organic UAA equalled 2.2 million ha, which represented 8.4 % of the total UAA in this study). We also calibrated the conventional system in the ALPHA-national model so that estimates for the entire system matched the statistical data on crops (yields and areas) and livestock (numbers and production) available at the national scale for 2021, including organic and conventional agriculture (Agreste, 2023a, 2024d; FAOSTAT, 2024a). For the conventional system, we obtained data specific to conventional crops (yields and areas) and livestock (numbers and production) by subtracting the previous estimates for organic crops and livestock from national statistical data that aggregated both types of agriculture (Agreste, 2023a, 2024d; FAOSTAT, 2024a). The ALPHA-national model contains multiple input and output variables for the organic ($_{org}$) (Table S3), conventional ($_{conv}$) (Table S4) and entire agricultural system ($_{tot}$) (conventional and organic) (Table S5). All input and output variables are described in the next section.

2.2.1. *Input variables of the model for the conventional system*

2.2.1.1. Cropland, grassland and animal production data. The area of conventional agriculture in 2021 studied (UAA_{conv}, 24.6 million ha) included conventional cropland and grassland. A forage category in crops included fodder cabbage, roots and tubers, fodder maize, fodder peas, fodder faba bean, lupin forage, vetch forage, beetroot, legumes mixtures and other forages. Artificial grasslands included clover, lucerne and sainfoin. The percentage of grassland in the total conventional UAA (τ) (45 %) was estimated from (Agreste, 2024d). The number of each species of livestock came from Agreste (2023a), from which we subtracted organic livestock to estimate the number of conventional livestock (Table S1).

Crop yield (Y_{crop_conv}) (124 kg N ha^{-1} yr^{-1}) was calculated from the overall mean yield of each crop, weighted by its cultivated area (Agreste, 2024d), and the N content of each crop from Lassaletta et al. (2014). We subtracted the area of OA (Data.gov (2021) from national statistics on total UAA (Agreste, 2024d) and organic crop yields (Vergely et al., 2024) from national statistics on crop yields (Agreste, 2024d).

The percentage of crop residues used for animal feed ($\alpha_{residues}$) (4 %) was an input estimated from national crop residues used in feed provided by Sailley et al. (2021) and Adams et al. (2019). We assumed an N harvest index of 70 % (Chatzimpiros and Harchaoui, 2023).

Feed imports ($r_{import\_feed\_conv}$) (10 kg N ha^{-1} yr^{-1}) were calculated using data from FAOSTAT (2024c) for France. Net feed imports were estimated by subtracting exports of soya bean, sunflower, rapeseed, soya bean cake, rapeseed cake, and sunflower cake from total imports of these commodities. In addition, organic feed imports estimated by Vergely et al. (2024) were subtracted to estimate the feed imports specific to conventional agriculture.

Livestock N conversion efficiency (NCE_{conv}) (18 %) was estimated based on the total N excreted by livestock from FAOSTAT (2024b) divided by the total N in livestock production from FAOSTAT (2024a).

2.2.1.2. Nitrogen cycling. The mean rate of atmospheric N deposition (r_{atm_conv}) (12 kg N ha^{-1} yr^{-1}) (Einarsson et al., 2021) was assumed to be the same in cropland ($r_{atm\_crop\_conv}$) and grassland ($r_{atm\_grass\_conv}$). We multiplied it by the area of each and then summed the products to calculate total atmospheric N deposition on conventional UAA.

Rates of BNF in cropland ($r_{BNF\_crop\_conv}$) (8 kg N ha^{-1} yr^{-1}) was an input estimated as weighted means using the method of Lassaletta et al. (2014) for each crop species of vegetables, oilseeds, protein crops and forages that could perform BNF (Supplementary Methods no. 2 and Table S6).

Rates of BNF in grassland ($r_{BNF\_grass\_conv}$) (20 kg N ha^{-1} yr^{-1}) was a weighted average for permanent, temporary and artificial grassland and was an input calculated from the percentage of legume cover in grassland and the BNF rate per legume. We set the percentage of legume cover in permanent, temporary and artificial grassland at 10 %, 20 % and 80 %, respectively (Schneider and Huyghe, 2015; Agreste, 2024c) (Supplementary Grassland definitions) and the BNF rate of legumes at 150 kg N ha^{-1} yr^{-1} (Chatzimpiros and Harchaoui, 2023), which correspond to pure legume crop (i.e. alfalfa or red clover). The percentage of legume cover by the BNF rate of legumes (150 kg N ha^{-1} yr^{-}1) calculates the BNF rate of each type grassland. Details for rates of BNF in permanent, temporary and artificial grassland are described in Table S7. Sensitivity analysis of this BNF rate was performed later (section 2.4).

The industrial fertiliser rate (r_{ind_conv}) (80 kg N ha^{-1} yr^{-1}) used in France in 2021 was an input calculated from the total industrial N fertiliser use reported by FAOSTAT (2023) assuming that 86 % was applied to cropland (14 % to grassland) (Floreal, 2021).

The percentage of N excreted in grassland (γ_{conv}) (45 %) was an input calculated from livestock excretion during grazing ($N_{manure\_grass\_conv}$, kg N ha^{-1} yr^{-1}) divided by total livestock excretion (N_{manure_conv}, kg N ha^{-1} yr^{-1}). We estimated total livestock excretion and the annual grazing time for each species based on the study of Floreal (2024). The percentage of manure N recovered from barns to fertilise cropland (β_{conv}) (63 %) was an input calculated from the time spent in barns by each species under French rearing conditions, which had been estimated to calculate N surpluses and stocks in barns (Table S8) (CORPEN, 2004, 2006; Giovanni, 2008; Idele, 2015). N surpluses and stocks in barns were defined as N that was lost in the barns and was not available or recoverable for cropland application. $N_{manure\_crop\_conv}$ (kg N ha^{-1} yr^{-1}) corresponds to manure used to fertilise cropland, while $N_{manure\_avail\_conv}$ (kg N ha^{-1} yr^{-1}) corresponds to manure available for cropland application, which was calculated as N_{manure_conv} minus $N_{manure\_grass\_conv}$ and N surpluses and stocks in barns. See Supplementary Method no. 3 for the equations used to calculate N_{manure}, N_{manure_crop} and N_{manure_grass}.

The N-use efficiency (NUE) of cropland (NUE_{crop_conv}) (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. Because the NUE of grassland (NUE_{grass_conv}) is little documented in the scientific literature, we assumed a value of 70 % for permanent, temporary and artificial grassland.

2.2.2. *Output variables of the model of the conventional system*

Grass yield (Y_{grass_conv}) (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 (i.e. atmospheric N deposition, BNF and industrial fertiliser) plus livestock excretion during grazing. The grassland yield was therefore the overall mean yield of permanent, temporary and artificial grasslands weighted by their UAA. We verified calculations for conventional grassland yields (Agreste, 2024d) (Table S9).

The weighted national mean percentage of crop production used for animal feed (α_{crop_conv}) (%) to meet the animals' feed requirements was calculated as an output of the model.

$N_{food\_animal\_conv}$ and $N_{food\_crop\_conv}$ (kg N ha^{-1} yr^{-1}) were animal- and crop-based human food, respectively, consumed in France or exported.

N input (N_{input_conv}, kg N ha^{-1} yr^{-1}) was the sum of atmospheric N deposition, BNF, industrial fertiliser and feed imports from abroad divided by conventional UAA.

N output (N_{output_conv}, kg N ha^{-1} yr^{-1}) corresponds to the total N contained in animal and crop agricultural products. N output was the sum of $N_{food\_animal\_conv}$ and $N_{food\_crop\_conv}$ divided by conventional UAA and corresponded to the total food yield (Y_{food_conv}, kg N ha^{-1} yr^{-1}) from conventional agriculture.

Total NUE (NUE_{conv}, %) was the system's total NUE.

N surpluses ($N_{surplus\_conv}$, kg N ha^{-1} yr^{-1}) equalled N inputs minus N outputs.

N self-sufficiency ($N_{self\ sufficiency\_conv}$, %) equalled the natural N inputs (i.e. atmospheric N deposition and BNF) divided by N_{input_conv} (Harchaoui and Chatzimpiros, 2019).

2.3. Regulatory background and design of scenarios

The scenarios for 2030 were built to meet the EU target of 25 % of agricultural land under OA (Fig. 2), using 2021 as the baseline year. We assumed that the total UAA in France (UAA_{tot}) in 2021 (26.9 million ha) would not change, for sustainability and biodiversity reasons (Pereira et al., 2010; Espon, 2020; Data.gov, 2023), and that crop rotations would remain the same. We therefore increased the organic UAA to 25 % of UAA_{tot} (i.e. 6.7 million ha) and decreased the conventional UAA to 75 % (i.e. 20.2 million ha) (Fig. 2) (Agreste, 2024d).

We developed two scenarios to illustrate possible pathways for the development of organic and conventional livestock, distinguishing ruminants and monogastric animals (Fig. 2). We separated monogastric animals into chickens and pigs to increase representativeness. We based the scenarios on the number of animals per species in LUs (Supplementary Livestock Units and Tables S10, S11 and S12). We assumed that the human population of France (65.5 million in 2021) (Insee, 2024) would increase to 67.0 million in 2030 (UNEP, 2024). We also assumed that food consumption, which corresponds to animal- and crop-based human food, was 4.68 and 2.48 kg N per capita per year, respectively (FAOSTAT, 2024c), and would remain the same in the BAU and HL scenarios. In both scenarios, we assumed that all organic animal- and crop-based human food production was consumed in France and all exported or imported animal- and crop-based human food production was conventional. We also assumed that changes in scenarios would be accompanied by corresponding changes in agricultural practices, ensuring that NUE_{crop} remained constant and equivalent to that of the baseline. We analysed total agricultural production by comparing it to its uses (e.g. food consumption, exports, other uses), particularly when production exceeded food consumption. The categories for exports and other uses of animal and crop products include feed, seeds, losses and other uses.

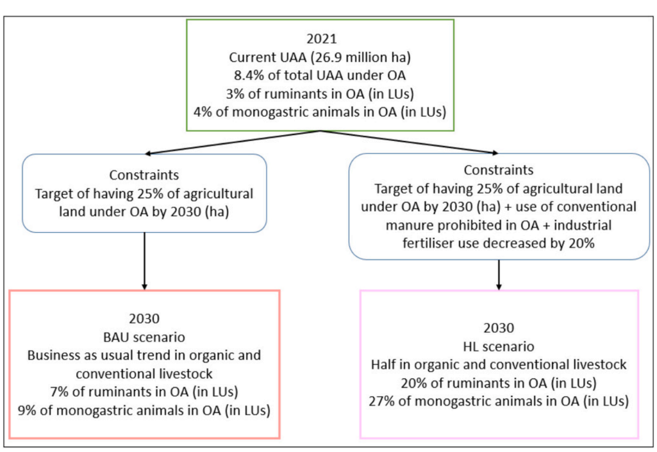

Fig. 2. Construction of the business as usual (BAU) and half livestock (HL) scenarios for 2030 (red and pink boxes) based on the baseline (green box) of organic agriculture (OA) and conventional agriculture in France in 2021 and the addition of regulatory objectives (blue box). UAA: utilised agricultural area, LUs: livestock units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3.1. Scenarios

2.3.1.1. Business as usual scenario. The "business as usual" (BAU) scenario continued the trend in each livestock species based historical data from 2017 to 2021 (Agreste, 2024d) (Table 1). We predicted the dynamics of each species by multiplying its population by the annual rate of change to estimate the number of animals in 2030 (Fig. 3b).

We assumed that feed imports for OA increased by the same percentage as the mean increase in organic monogastric animals (Tables 1 and S13). We assumed that organic ruminants were not included in these changes, as they were fed mainly green fodder from organic cropland. Conversely, for conventional agriculture, we assumed that feed imports decreased by the same percentage as the mean decrease in the numbers of conventional animals (both ruminants and monogastric animals) (Tables 1 and S13).

2.3.1.2. "Half livestock" scenario. In the "half livestock" (HL) scenario,

Table 1
Characteristics of the baseline (2021) and the business as usual (BAU) and half livestock (HL) scenarios for the expansion of organic agriculture (OA) in France in 2030. Ruminants were dairy cattle, beef cattle, dairy ewes, meat ewes and dairy goats). Monogastric animals were broiler chickens, laying hens and pigs. We assumed that the total utilised agricultural area (UAA) in the BAU and HL scenarios would not change and that crop rotations would remain the same.

Scenario	Baseline	BAU	HL
Human population	65.5 million	67.0 million	67.0 million
Utilised agricultural area	26.9 million ha	26.9 million ha	26.9 million ha
Percentage of organic land	8.4 %	25 %[1]	25 %[1]
Trends in the number of livestock	NA	projected increase in each organic and conventional livestock species from 2017 to 2021	50 % decrease in the number of livestock, and number of organic livestock increased by the same percentage as organic UAA
Feed imports	NA	increased by the same percentage as the mean increase in the number of organic monogastric animals and decreased by the same percentage as the mean decrease in the number of conventional livestock	no organic feed imports in OA, and feed imports decreased by the same percentage as the mean decrease in the number of conventional livestock
Use of conventional manure in OA	allowed	allowed	prohibited[2]
Industrial fertiliser use	NA	not changed	decreased by 20 %[3]

NA: not applicable.
[1] Target of the EU Green Deal of having 25 % of agricultural land under OA by 2030.
[2] Assumed an EU prohibition on the use of conventional manure in OA.
[3] Target of the EU Green Deal of decreasing industrial fertiliser use by at least 20 %.

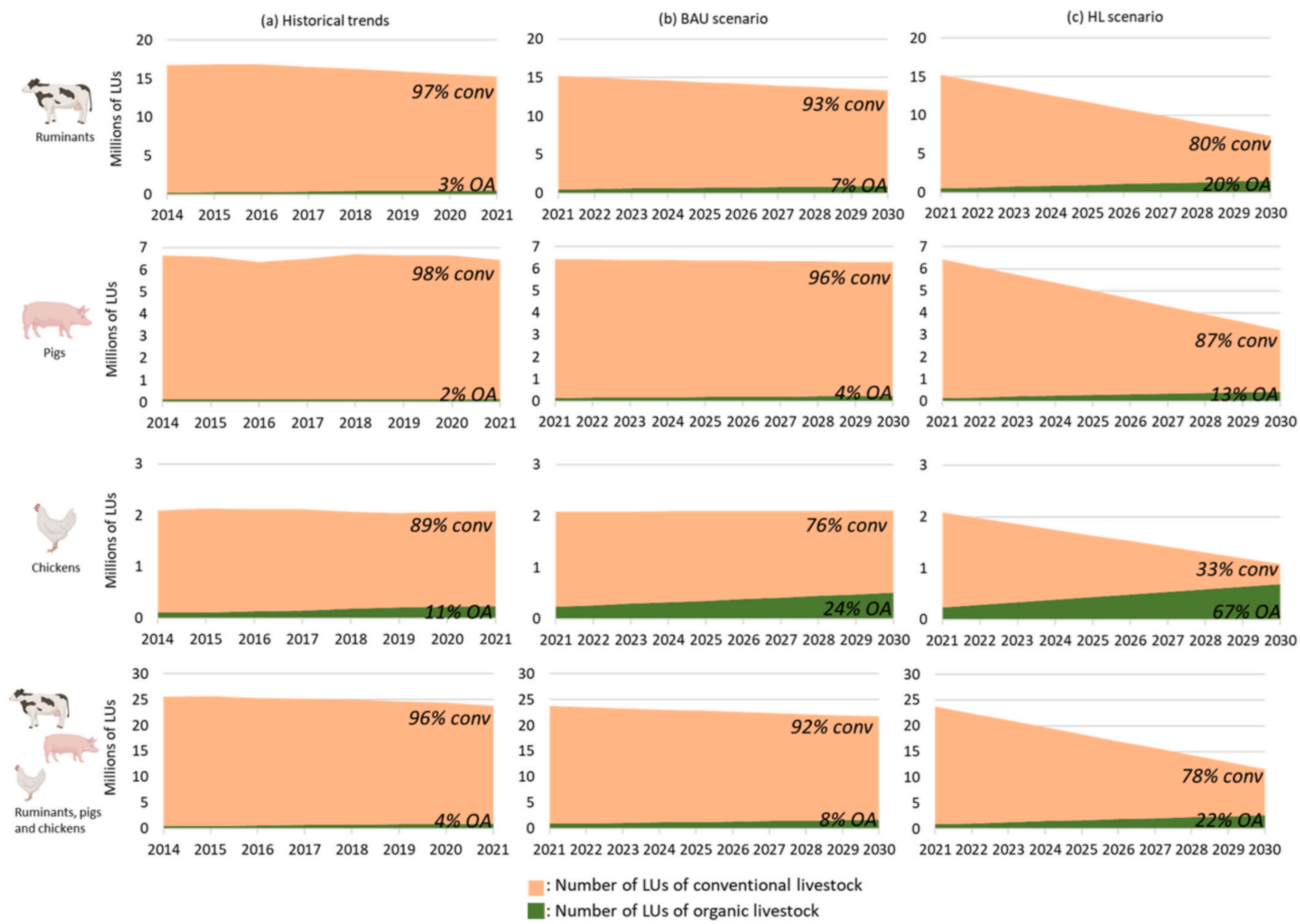

Fig. 3. (a) Historical trends from 2014 to 2021 (Agreste, 2023a; AgenceBio, 2025) and predicted trends from 2021 to 2030 for the (b) business as usual (BAU) scenario and (c) half livestock (HL) scenario in ruminants (dairy cattle, beef cattle, dairy ewes, meat ewes and dairy goats), pigs and chickens (broiler chickens and laying hens) in livestock units (LUs). Percentages indicate the predicted percentages of organic (OA) and conventional (conv) livestock out of all livestock in 2030.

we first decreased the total (organic and conventional) number of each livestock species by 50 % compared to 2021 (Fig. 3c). We then assumed that the percentage of organic livestock of each species increased by the same number of percentage points as the percentage of organic UAA had, and that the remaining livestock were conventional (Tables 1 and S12, Fig. 3c). This scenario was based on many recent studies that recommended a drastic decrease (i.e. 50–90 %) in human consumption of animal products (Poore and Nemecek, 2018; Springmann et al., 2018; Billen et al., 2021; Ademe, 2022).

We assumed an EU prohibition on the use of conventional manure in OA, which contrasted with the baseline and BAU scenario, in which it could be used if it came from non-industrial livestock farms (Annex II of EU Regulation (2018/848)). In conventional agriculture, we applied another EU Green Deal target by decreasing industrial fertiliser use by 20 % (Table 1).

We assumed no organic feed imports in OA (Table S13) in order to develop a self-sufficient organic system. Like in the BAU scenario, we assumed that conventional feed imports decreased by the same percentage as the mean decrease in the numbers of conventional animals (Tables 1 and S13).

2.4. Sensitivity analysis

BNF of legumes in grassland plays a critical role in N cycling but it has high variability and uncertainty, particularly at larger spatial scales (Zhang et al., 2021), which makes it difficult to assess it consistently across studies (Barbieri et al., 2023). To explore the influence of changing legume BNF on model predictions, we performed a sensitivity analysis of the baseline and the BAU and HL scenarios. Specifically, we increased the BNF rate of legumes from 150 to 200 kg N ha^{-1} yr^{-1} in both organic and conventional grasslands, keeping all other parameters constant. This approach allowed us to assess the sensitivity of N flows to changes in the legume BNF rate in different scenarios.

2.5. Definition of nitrogen indicators

We summarised the performance of the organic, conventional and the entire agricultural system using eight indicators of N (i.e. mean crop yield (Y_{crop}), total N input (N_{input}), total N contained in animal and crop agricultural products (N_{output}), N in animal-based human food (N_{food_animal}), N in manure available for cropland application (N_{manure_avail}), N surpluses ($N_{surplus}$), NUE and N self-sufficiency ($N_{self\_sufficiency}$)) (Table 2).

3. Results

3.1. Change in livestock in the two scenarios

Compared to the baseline, the BAU scenario resulted in an overall decrease in the number of LUs of ruminants (−13 %) and pigs (−2 %) and a slight increase in the number of LUs of chickens (1 %) and thus an overall decrease of 9 % in the total number of LUs (Fig. 3b, Table S11),

Table 2
Definitions and equations of the nitrogen (N) indicators used to summarise the performance of organic, conventional and the entire agricultural system. All indicators are in kg N ha^{-1} yr^{-1} except for NUE and $N_{self\_sufficiency}$ (in %). N surpluses and stocks in barns correspond to N lost in the barns and not available or recoverable for cropland application. UAA: utilised agricultural area, BNF: biological nitrogen (N) fixation, N_{atm}: atmospheric N deposition, τ: percentage of grassland in UAA, NUE_{crop}: NUE of cropland, N_{ind}: industrial N fertiliser applied to cropland, N_{import_feed}: feed N imports from abroad, N_{manure_crop}: manure N used to fertilise cropland, N_{manure_grass}: manure N excreted on grassland, N_{food_crop}: N in crop-based human food, β: percentage of manure N recovered from barns to fertilise cropland.

Indicator	Definition	Equation
Y_{crop}	Mean crop yield	$Y_{crop} = \frac{NUE_{crop} \times (N_{crop\_atm} + N_{crop\_BNF} + N_{ind} + N_{manure\_crop})/1-\tau}{UAA}$
N_{input}	Total N input	$N_{input} = \frac{(BNF + N_{atm} + N_{import\_feed} + N_{ind})}{UAA}$
N_{output}	Total N in animal and crop products	$N_{output} = \frac{(N_{food\_animal} + N_{food\_crop})}{UAA}$
N_{food_animal}	N in animal-based human food	$N_{food\_animal} = \frac{(N_{output} - N_{food_{crop}})}{UAA}$
N_{manure_avail}	N in manure minus N in manure on grassland and N surpluses and stocks in barns	$N_{manure\_avail} = \frac{(N_{manure} - N_{manure\_grass} \times \tau) \times \beta}{UAA}$
$N_{surplus}$	N surplus	$N_{surplus} = N_{input} - N_{output}$
NUE	N-use efficiency	$\mathrm{NUE} = \frac{N_{output}}{N_{input}} \times 100$
$N_{self\_sufficiency}$	Natural N inputs divided by total N input	$N_{self\_sufficiency} = \left(\frac{BNF + N_{atm}}{UAA}\right) \Big/ N_{input} \times 100$

while in the HL scenario, as designed, the number of LUs decreased by 50 % (Fig. 3c). However, the percentage of organic livestock in the BAU and HL scenarios was higher (4–24 % and 13–67 %, respectively) than that in the baseline, depending on the species (Fig. 3). In the BAU scenario, the decrease in the number of LUs of conventional pigs (−4 %) and chickens (−14 %) was balanced by an increase in the number of organic pigs (+59 %) and chickens (+118 %), which resulted in nearly no change in the total number of LUs of monogastric animals (−1 %) (Table S11) (Fig. 3b). In the HL scenario, the number of LUs of organic livestock increased by 197 % in organic UAA, while the total number of LUs of livestock decreased by 50 % (Fig. 3c). The number of LUs of conventional ruminants and monogastric animals decreased by 59 % and 62 %, respectively, which resulted in a higher percentage of organic livestock than that in the baseline (Fig. 3c, Table S12).

3.2. Nitrogen flows for the entire agricultural system in France for the baseline and two development scenarios

Compared to the baseline, the indicators of N in agricultural products (Y_{crop_tot}, N_{output_tot} and $N_{food\_animal\_tot}$) in the BAU and HL scenarios were lower than those in the baseline (−9 % and − 27 %, respectively) (Table 3), due to the increase in organic crops and livestock, which were less productive. Productivity was lowest in the HL scenario due to the prohibition on the use of conventional manure in OA and 20 % decrease in industrial fertiliser use in conventional agriculture, which decreased Y_{crop_tot} by 24 % compared to that in the baseline. The increase in the number of organic livestock and decrease in the number of conventional livestock resulted in a lower $N_{food\_animal\_tot}$ in France in the BAU and HL scenarios (11 and 9 kg N ha^{-1} yr^{-1}, respectively). The changes in livestock numbers also decreased the availability of manure for fertilising cropland: $N_{manure\_avail\_tot}$ in the BAU and HL scenarios was 8 % and 28 % lower, respectively. The latter was due to the 50 % decrease in livestock numbers, which was not offset by the increase in the number of organic livestock and their associated higher manure production during grazing.

Table 3
Nitrogen (N) indicators for the entire agricultural system in France in the baseline (2021) and business as usual (BAU) and half livestock (HL) scenarios (2030). Y_{crop}: cropland yield, N_{input}: sum of atmospheric nitrogen (N) deposition, biological N fixation, industrial N fertiliser and feed imports, BNF: biological N fixation, N_{atm}: atmospheric N deposition, N_{ind}: industrial N fertiliser applied to cropland, N_{import_feed}: feed N imports from abroad, N_{output}: total N contained in animal and crop agricultural products, N_{food_animal}: animal-based human food, N_{manure_avail}: manure N available for cropland application, $N_{surplus}$: N inputs minus N outputs, NUE: N use efficiency and $N_{self\text{-}sufficiency}$: natural N inputs (i.e. atmospheric N deposition and BNF) divided by N inputs.

Indicator	Baseline	BAU	HL	Unit
Livestock unit density	0.90	0.82	0.45	LU ha^{-1}
Y_{crop_tot}	119	109	90	kg N ha^{-1} yr^{-1}
N_{input_tot}	112	102	81	kg N ha^{-1} yr^{-1}
BNF_{tot}	*14*	*19*	*23*	% of N_{input_tot}
N_{atm_tot}	*11*	*12*	*15*	% of N_{input_tot}
N_{ind_tot}	*66*	*59*	*59*	% of N_{input_tot}
$N_{import\_feed\_tot}$	*9*	*10*	*3*	% of N_{input_tot}
N_{output_tot}	47	43	33	kg N ha^{-1} yr^{-1}
$N_{food\_animal\_tot}$	12	11	9	kg N ha^{-1} yr^{-1}
$N_{manure\_avail\_tot}$	29	27	21	kg N ha^{-1} yr^{-1}
$N_{surplus\_tot}$	65	59	48	kg N ha^{-1} yr^{-1}
NUE_{tot}	42	42	39	%
$N_{self\_sufficiency\_tot}$	27	35	46	%

In both development scenarios, especially the HL scenario, the overall N-use efficiency was higher, with higher $N_{self\_sufficiency\_tot}$ and lower $N_{surplus\_tot}$ than those in the baseline. The HL scenario had the highest $N_{self\_sufficiency\_tot}$ (46 %) because it had the fewest conventional livestock, which relied mainly on imported feed, and imported no organic feed. Thus, modifying the fertilisation scheme in both systems increased N self-sufficiency. In the BAU and HL scenarios, total N_{input_tot} decreased by 9 % and 28 %, while the percentage of BNF_{tot} in N_{input_tot} increased by 32 % and 61 %, respectively. We estimated that 19 % in the total BNF of France was organic. $N_{surplus\_tot}$ in the HL scenario was estimated at 48 kg N ha^{-1} yr^{-1}, which although being 26 % lower than that in the baseline, remained short of the EU Green Deal target of a 50 % decrease in nutrient surpluses (i.e. target of 32 kg N ha^{-1} yr^{-1}).

3.3. Food production, consumption and exports in France

In the BAU and HL scenarios, the percentage of organic production (13 % and 9 %, respectively) and consumption (32 % and 17 %, respectively) were higher than those in the baseline (4 % of production and 10 % of consumption) (Fig. 4a).

In the BAU scenario, animal and crop production (Gg N yr^{-1}) decreased by 9 % and 10 %, respectively, which decreased total food production by 9 % compared to that in the baseline (Fig. 4b). In the organic system, animal production and crop production increased by a factor of 2.3 and 2.1, respectively, due to the increase in the number of organic livestock and organic UAA. As consumption trends remained similar to those in the baseline, domestic animal production was no longer sufficient to feed the larger French population, which required

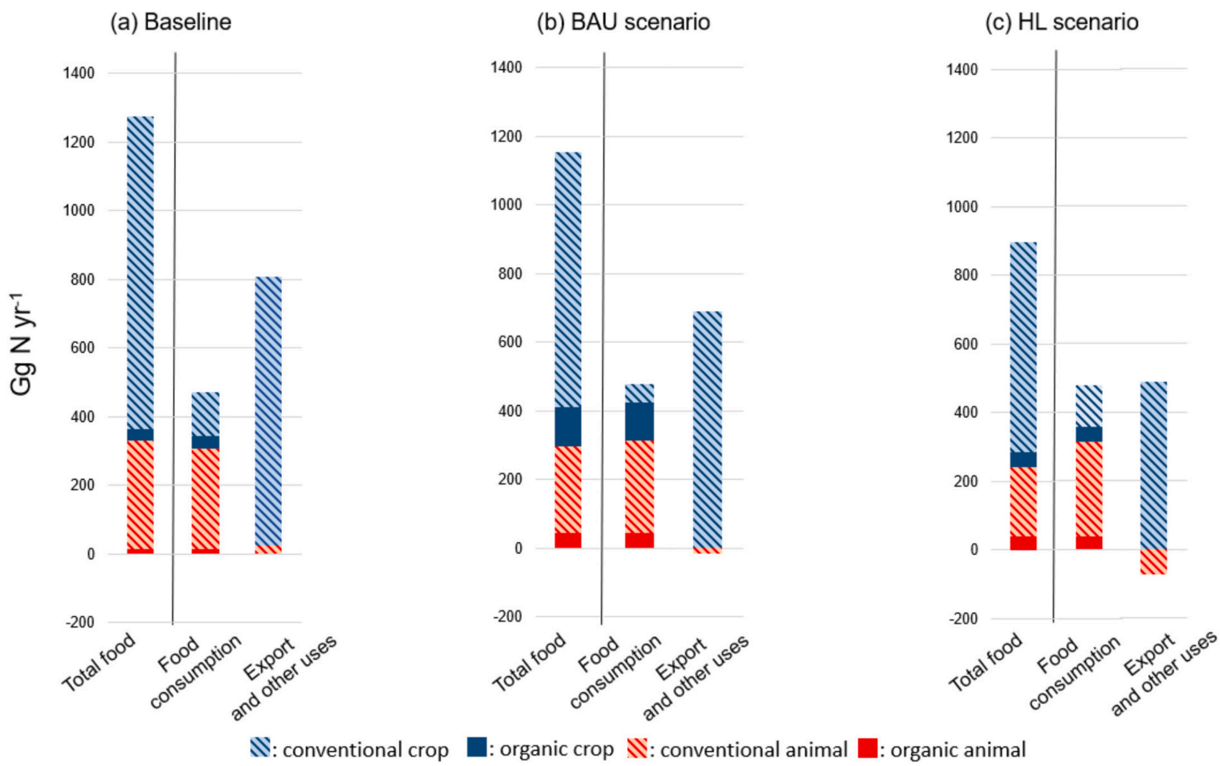

Fig. 4. Total food, food consumption and export of animal and crop products for organic and conventional agriculture in (a) the baseline (2021) and (b) business as usual (BAU) and (c) half livestock (HL) scenarios (2030). Total food corresponds to the sum of all animal and crop production for human food, consumed in France or exported (and other uses). Food consumption corresponds to animal- and crop-based human food consumption (4.68 and 2.48 kg N per capita per year, respectively) (FAOSTAT, 2024c). The French population was 65.5 million in the baseline and 67.0 million in the two development scenarios.

importing animal products (15 Gg N yr^{-1}) (Fig. 4b). Thus, this scenario indicated that if France wants to achieve 25 % agricultural land under OA without externalising negative environmental impacts to other countries through imports, its population needs to decrease its consumption of animal products by 5 %. For the crop-based products consumed, a higher percentage was organic (67 %) than conventional (32 %). Conventional crop exports decreased by 12 % compared to those in the baseline. Some of the conventional crop-based products could be consumed instead of exported to replace the deficiency in animal products (i.e. less animal protein and more crop protein in the human diet).

In the HL scenario, animal and crop production (Gg N yr^{-1}) decreased by 26 % and 31 %, respectively, due to the lower productivity of the agricultural system (Table 3), which decreased total food production by 30 % compared to that in the baseline (Fig. 4c). In the organic system, animal and crop production increased by 186 % and 22 %, respectively (i.e. lower than those in the BAU scenario). Like in the BAU scenario, domestic animal production was no longer sufficient to feed the larger French population. Consequently, even more animal products were imported in the HL scenario (71 Gg N yr^{-1}). To avoid importing them in this scenario, the consumption of animal products in the French diet would have to decrease by 30 %. For the crop-based products consumed, a lower percentage was organic (26 %) than conventional (74 %). Conventional crop exports decreased even more (−38 %) compared to those in the baseline (Fig. 4c).

3.4. Nitrogen performances for organic and conventional agriculture in the entire agricultural system

In the baseline and two development scenarios, OA had lower productivity than conventional agriculture did (Fig. 5b, d and e). Both systems had the lowest productivity in the HL scenario, in which N_{output_org} and N_{output_conv} were 44 % and 19 % lower than those in the baseline (Fig. 5d). This decrease was due to lower N input availability, as N_{input_org} and N_{input_conv} were 21 % and 20 % lower than those in the baseline, respectively (Fig. 5c), due to the prohibition on using conventional manure in OA and the 20 % decrease in industrial fertiliser use, which decreased N fertilisation of crops. Moreover, Y_{crop_org} and Y_{crop_conv} were 13 % and 18 % lower in the HL scenario than in the baseline, respectively (Fig. 5b). Specifically for OA, Y_{crop_org} was 7 % higher in the BAU scenario and 13 % lower in the HL scenario, even though $N_{manure\_avail\_org}$ (i.e. manure available for cropland application) was 20 % and 11 % higher than that in the baseline, respectively (Fig. 5f). In both scenarios, the number of organic livestock increased, which maintained the availability of organic manure. However, in the HL scenario, the prohibition on using conventional manure in OA and the fact that organic livestock were no longer fed imported feed decreased manure production and did not compensate for the increase in the number of organic livestock and consequent decrease in organic crop yields. Moreover, in OA in the HL scenario, the percentage of organic crop production used for animal feed had to increase from 37 % to 72 % to meet the increased demand for feed of more organic livestock. Thus, the HL scenario for OA increased the competition between food and feed, but maintained $N_{food\_animal\_org}$ production without importing organic animal feed (Fig. 5e). In addition, the increase in the number of organic or conventional ruminants and monogastric animals played a key role, as organic livestock excreted more during grazing due to longer grazing periods (mean of 69 % and 17 % longer, respectively) than those of conventional livestock (mean of 58 % and 4 % longer, respectively). In the HL scenario, $LUs_{\_org}$ was 197 % higher than that in the baseline because the number of organic livestock increased by the same percentage as the organic UAA (Fig. 5j).

In the HL scenario, N self-sufficiency in OA (Fig. 5i) was higher than that in the BAU scenario. $N_{self\text{-}sufficiency\_org}$ and $N_{self\text{-}sufficiency\_conv}$ were 26 % and 25 % higher in the HL scenario, respectively (Fig. 5i), due to the 20 % decrease in industrial fertiliser use, the decrease in feed imports by

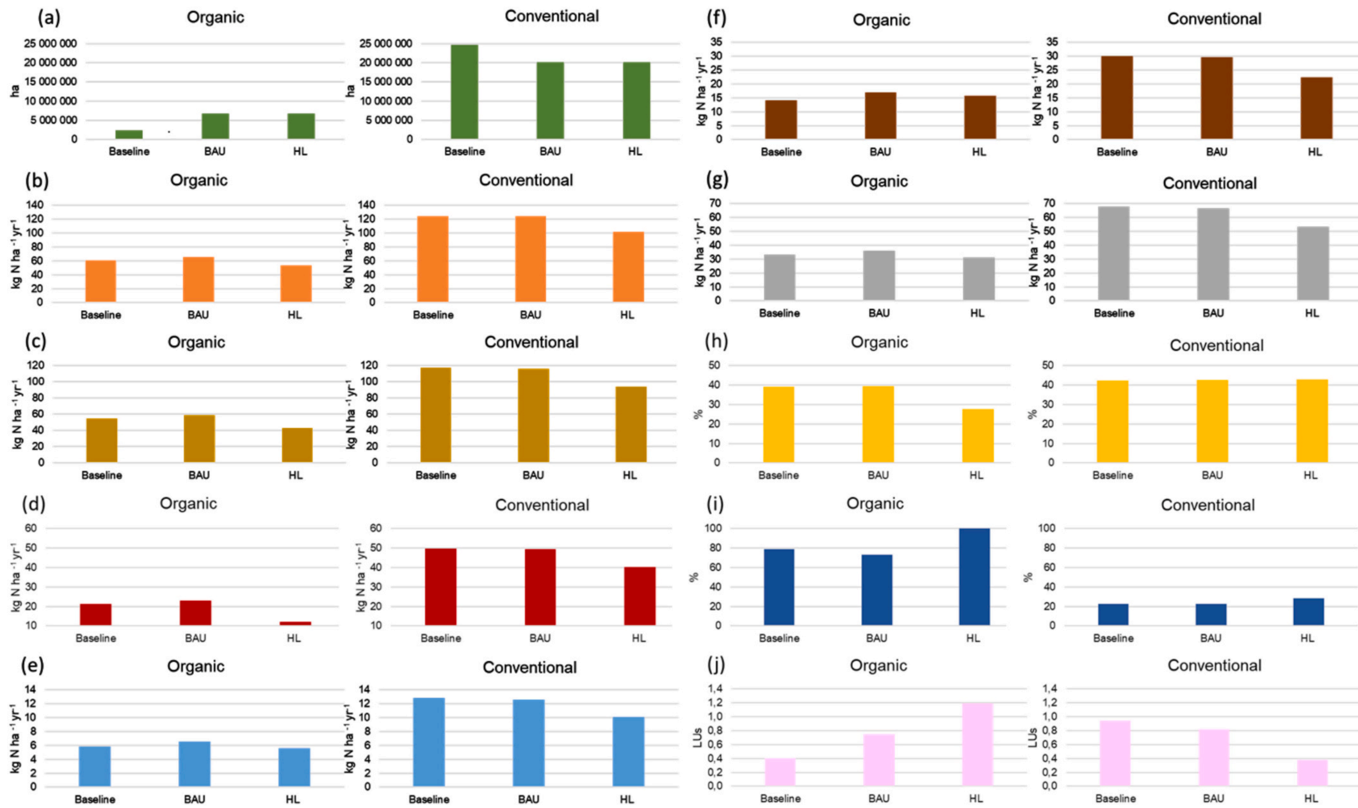

Fig. 5. Nitrogen (N) indicators for organic ($_{org}$) and conventional ($_{conv}$) agriculture in the entire agricultural system in the baseline (2021) and business as usual (BAU) and half livestock (HL) scenarios (2030): (a) utilised agricultural area (UAA), (b) Y_{crop}: cropland yield, (c) N_{input}: sum of atmospheric N deposition, biological N fixation, industrial N fertiliser and feed imports, (d) N_{output}: total N contained in animal and crop agricultural products, (e) N_{food_animal}: animal-based human food, (f) N_{manure_avail}: manure N available for cropland application, (g) $N_{surplus}$: N inputs minus N outputs, (h) NUE: N use efficiency, (i) $N_{self\_sufficiency}$: natural N inputs (i.e. atmospheric N deposition and BNF) divided by N inputs and (j) livestock units (LUs). See Table 2 for definitions of indicators.

100 % in OA and 69 % in conventional agriculture, and the prohibition on the use of conventional manure in OA. Conversely, in the BAU scenario, $N_{self\text{-}sufficiency\_org}$ was 7 % lower than that in the baseline due to the changes in feed imports (+88 %) made to meet ruminant and monogastric animal requirements (Table S13). Conversely, NUE_{org} was 29 % lower in the HL scenario than that the baseline, mainly due to organic livestock having a low NCE (13 %) and the higher percentage of animal production in total production in the HL scenario for OA (47 %) than that in the baseline for OA (27 %). In addition, compared to those in the baseline, $N_{surplus\_org}$ and $N_{surplus\_conv}$ were 6 % and 21 % lower in the HL scenario, respectively, but 8 % higher and 2 % lower in the BAU scenario, respectively (Fig. 5g).

3.5. Sensitivity analysis of the biological nitrogen fixation rate of legumes

The sensitivity analysis indicated that increasing the BNF rate of legumes from 150 to 200 kg N ha^{-1} yr^{-1} increased grassland yield and thus production of animal food production and manure (Table 4). Specifically, increasing it in the baseline and BAU and HL scenarios increased Y_{grass_tot} by 11 %, 13 % and 14 %, respectively, and Y_{crop_tot} by only 0.2 %, 1 % and 2 %, respectively. The percentage of BNF_{tot} in N_{input_tot} increased in the baseline and BAU and HL scenarios by 18 %, 13 % and 15 %, respectively. Thus, the main changes in the BAU and HL scenarios were that $N_{food\_animal\_tot}$ increased by 6 % and 8 %, respectively, and $N_{manure\_avail\_tot}$ increased by 4 % and 6 %, respectively, because livestock feed was increased by the higher grassland production. However, in the BAU and HL scenarios, $N_{surplus\_tot}$ increased by 5 % and 6 %, respectively, mainly due to more fodder being used to feed livestock, which were less efficient (17 %) than crops (65 %). Results of the BAU and HL scenarios indicated that increasing legumes was a promising path to provide more N to cropland and maintain cropland yield with less manure from livestock. See Table S14 and S15 for results of the sensitivity analysis for organic and conventional agriculture, respectively.

Table 4
Sensitivity analysis of effects on nitrogen indicators of increasing the rate of biological nitrogen (N) fixation (BNF) of legumes from 150 to 200 kg N ha^{-1} yr^{-1} for organic and conventional grassland in the baseline (2021) and business as usual (BAU) and half livestock (HL) scenarios (2030) in total agriculture. The "% change" columns show the percentage change in the indicators compared to those in the initial baseline and the BAU and HL scenarios. All indicators are in kg N ha^{-1} yr^{-1} except for NUE and $N_{self\_sufficiency}$ (in %). See Table 2 for definitions of indicators.

Indicator	Baseline	% change	BAU	% change	HL	% change
Y_{crop_tot}	119	+0.2 %	110	+1 %	91	+2 %
Y_{grass_tot}	69	+11 %	68	+13 %	63	+14 %
N_{input_tot}	115	+3 %	106	+4 %	85	+5 %
BNF_{tot}	*17*	+18 %	*21*	+13 %	26	+15 %
N_{atm_tot}	*10*	−3 %	*12*	+1 %	14	−4 %
N_{ind_tot}	*64*	−3 %	*57*	−4 %	57	−5 %
$N_{import\_feed\_tot}$	*9*	−2 %	9	−8 %	3	−6 %
N_{output_tot}	48	+1 %	44	+2 %	34	+3 %
$N_{food\_animal\_tot}$	13	+4 %	12	+6 %	10	+8 %
$N_{manure\_avail\_tot}$	30	+3 %	28	+4 %	22	+6 %
$N_{surplus\_tot}$	68	+4 %	62	+5 %	51	+6 %
NUE_{tot}	41	−2 %	41	−2 %	39	−1 %
$N_{self\_sufficiency\_tot}$	29	+7 %	38	+6 %	48	+4 %

In addition, considering the baseline with a BNF rate of legumes at 150 kg N ha^{-1} yr^{-1} and the BAU and HL scenarios with a BNF rate of legumes at 200 kg N ha^{-1} yr^{-1}, animal production would be sufficient to meet food requirements of the French population in the BAU scenario, with the potential to export 4 Gg N yr^{-1}. In the HL scenario, it would be necessary to import only 51 Gg N yr^{-1} to meet the population's demand for animal products; thus, the consumption of animal products in the French diet would have to decrease by 20 % instead of 30 %.

4. Discussion

4.1. Influence of the human diet on the development of organic agriculture

The results highlighted the N trade-offs necessary to meet development goals for OA in France while maintaining the current consumption of animal products, which would require importing more of them (Fig. 4). Consumption of animal products shows no sign of decreasing in France, where for the second consecutive year in 2022, total consumption of animal products increased (+0.8 % per year) (Agreste, 2023e). Thus, animal products still represent more than 33 % of the total protein consumed in France. In the BAU and HL scenarios, 25 % of agricultural land under OA with no change in French dietary trends resulted in importing more animal products (15 and 71 Gg N yr^{-1}, respectively) and decreasing cereal exports by 12 % and 38 %, respectively, compared to those in the baseline (Fig. 4). These results agreed with those of Borghino et al. (2024), for which most of the scenarios in which food self-sufficiency was not achieved corresponded to current or projected diets with high calorie intake and a high percentage of animal products in the diet. Conversely, in the Billen et al. (2018) scenario of the French agri-food system, which generalised OA practices, reconnected crop and livestock sub-systems and decreased consumption of animal protein by 50 %, changes in the diet allowed future national food demand to be met without importing food, and France decreased its exports of cereals greatly (−59 %). According to previous studies, changing human diets was a stronger potential pathway for increasing agricultural N productivity, N self-sufficiency and biophysical options for expanding OA than changing livestock numbers or yields (Erb et al., 2016). However, Morais et al. (2021) found that the feasibility of expanding OA in the face of N constraints requires agroecological and circular economy improvements and was increased by the presence of a moderate amount of animal products in the diet, specifically vegetarian diets that include milk and eggs. However, decreasing the amount of animal-based food in human diets is a necessary but not sufficient condition (Darmon et al., 2024), due to subsequent trade-offs in the N budget (Morais et al., 2021). In agreement with Morais et al. (2021), scenarios in the present study highlighted these trade-offs, with fewer livestock producing less manure that was available to fertilise crops, which decreased yields.

To decrease imports of animal products in the BAU and HL scenarios, consumption of animal products should be decreased by 5 % and 30 %, respectively. However, even when OA represented only 8.4 % of the UAA, food imports were already a major concern for the French agricultural system (Chatellier and Pouch, 2021). For certain animal products, production is already insufficient to meet consumption; thus, imports are necessary. For example, consumption of poultry (especially chickens) has increased by 17 % since 2000 (Agreste, 2024a), and poultry is now the meat consumed most in France (Agreste, 2023d) (Table S16). Because domestic chicken production does not meet domestic consumption (ChambreAgriculture, 2023), chicken imports continue to increase (+8 % in carcass equivalent from 2022 to 2023) (Itavi, 2023), which increases the foreign trade deficit. These trends contribute to the increase in the prices of animal products (EC, 2022). Conversely, excluding tropical products, 83 % of the organic food consumed in France was produced in France (AgenceBio, 2023). Self-sufficiency of the French organic sector is an advantage at a time when French consumers are paying more attention to the origin of products, which is the most important factor for them after price (AgenceBio, 2023). However, purchases of organic food in France decreased by 4.6 % from 2021 to 2022, especially of organic meat (−13 %) (AgenceBio, 2023), as unprecedented inflation and the COVID-19 pandemic forced consumers to make new trade-offs in their purchasing decisions (Chatellier, 2024). Thus, in France, there was a contradiction between the increasing consumption of animal products but decreasing consumption of organic animal products, while the number of conventional livestock was decreasing and the number of organic livestock was increasing (Fig. 3b).

4.2. Changes in livestock numbers in organic agriculture scenarios

Only a few scenarios of the development of OA at the national scale exist that considered organic and conventional livestock trends; thus, comparisons were limited. In the BAU scenario, we estimated that the number of LUs decreased by 13 % for ruminants and 1 % for monogastric animals (i.e. decrease of 9 % in the total number of LUs) (Fig. 3b, Table S11). The review of Borghino et al. (2024) summarised the main trends in livestock numbers in OA scenarios and found an overall mean decrease of 28 % in the number of LUs between the baseline situation and the expansion of OA. In the scenario of Billen et al. (2018), the number of livestock decreased greatly but was much more evenly distributed among the regions of France; its minimum decrease of 0.5 LU ha^{-1} UAA was slightly higher than the mean decrease that we estimated in the HL scenario (0.45 LU ha^{-1} UAA). In a scenario of 25 % of agricultural land under OA in Slovenia developed by Drofenik et al. (2023), due to OA regulations, not enough poultry feed was produced, so the number of chickens decreased by 42 %. The number of organic cattle increased by 60 % compared to that in the baseline situation, however, as organic cattle were fed mainly green fodder from cropland.

However, differences in modelling assumptions for livestock trends and feed systems between the development scenarios in the present study and those of other agri-food scenarios (Billen et al., 2018; Drofenik et al., 2023; Borghino et al., 2024) may have been due to the constraints applied to the scenarios. Agri-food scenarios can consider multiple constraints simultaneously, such as the large-scale expansion of OA, food supply and demand, environmental performance, self-sufficiency, livestock numbers, decrease in surpluses, animal products in diets, food waste and GHG emissions. The constraints of the BAU scenario in the present study were used to produce visions of future agricultural systems with 25 % of agricultural land under OA if some of the current trends were pushed to their logical limits, like in the scenarios of Billen et al. (2018). In the HL scenario, we included additional changes, as Muller et al. (2017) and Morais et al. (2021) did, for the number of livestock or fertilisation scheme, and estimated trade-offs between the large-scale expansion of OA and a large decrease in livestock production. In the development scenarios of this study, we tailored feed strategies to align with the livestock trends observed. Specifically, in the HL scenario, in which feed imports from abroad were prohibited in OA, the percentage of organic crop production used for animal feed increased greatly from 37 % to 72 % to accommodate the increased demand of more organic livestock. Model predictions indicate that if livestock NCE in OA is not increased, maintaining the current degree of feed-food competition — i.e., keeping the percentage of organic crop production used for animal feed at 37 % — would restrict the potential increase in organic livestock to 135 % instead of the 197 % increase projected in the HL scenario. Otherwise, livestock numbers can be adjusted as a function of feed availability, as in the scenario of Drofenik et al. (2023). In pursuing certain OA scenarios (Couturier et al., 2016; Barbieri et al., 2021), we attempted to assess the overall livestock trend more precisely by distinguishing trends in organic and conventional livestock. However, for the first time, from 2022 to 2023, the number of every species of organic animal except sheep decreased (AgenceBio, 2025). This trend is not represented in any of the OA scenarios and reflects the initial signs of a decrease in organic production and consumption caused by difficult geopolitical and economic contexts that were not expected in the scenarios developed to date.

From an environmental perspective, OA scenarios may shift towards monogastric animals because ruminants contribute more to GHG emissions than monogastric animals do (Zervas and Tsiplakou, 2012) but ruminants conserve grasslands while maintaining soil quality to decrease land degradation (Milazzo et al., 2023) and the associated biodiversity loss (Veen et al., 2009; Poux and Aubert, 2022; Klaus et al., 2024). From a nutrient perspective, OA scenarios shift towards ruminants because ruminants transfer nutrients from grasslands to croplands and decrease feed-food competition. N self-sufficiency is a major concern in conventional agriculture (Dronne, 2019) and to a lesser extent in OA for monogastric animals (Montagne et al., 2024) due to the dependence on imported feed and feed crops that results in competition for land that can be used to produce food (Van Zanten et al., 2019). However, the 13 % decrease in ruminants and 1 % decrease in monogastric animals in the BAU scenario would not increase N self-sufficiency unless the latter are fed less imported feed. Conversely, Borghino et al. (2024) reported a mean decrease of 13 % in ruminants and 51 % in monogastric animals. These results agree with those of the Agora Agriculture (2024) scenario for the EU in 2045, in which monogastric animals decreased (−67 %) more than ruminants did (−52 %). To feed animals without depending too much on imports, mainly for protein (i.e. soya beans and soya bean cake), France needs large areas of forage and large amounts of concentrated raw ingredients. Over the past 50 years, however, global demand for animal products has increased, which has greatly increased the percentage of agricultural land used to produce feed (Thornton, 2010; Davis and D'Odorico, 2015). In the present study, we did not change the composition or duration of crop rotations, but doing so would be an interesting option to explore in future scenarios to decrease dependence on imported feed.

4.3. Performance of organic crops and livestock

OA has lower yields (Seufert and Ramankutty, 2012) and thus requires more land to produce the same amounts as conventional agriculture (Muller et al., 2017). In the BAU and HL scenarios, cereal production (Gg N yr^{-1}) decreased by 10 % and 31 %, respectively, while in the Billen et al. (2018) scenario, cereal production increased by 64 %. For the HL scenario, this result was due to the 25 % of agricultural land under OA and the change in the fertilisation scheme of cropland. In addition, because there were 50 % fewer animals, one way to maintain organic yields was to increase BNF (Mäder et al., 2002) by adding perennial forage crops (i.e. legumes) to annual crop rotations, which can decrease N requirements per ha (Morais et al., 2021). Compared to a non-legume as a preceding crop in a rotation, a legume (e.g. beans, lucerne, clover) can provide N to subsequent crops through BNF. BNF can be increased mainly by increasing BNF rates or adjusting the duration of crop-legume rotations. The sensitivity analysis indicated that in the HL scenario, increasing the BNF rate of legumes from 150 to 200 kg N ha^{-1} in grasslands would increase organic crop yield from 53 to 57 kg N ha^{-1} yr^{-1}, organic grassland yield from 43 to 53 kg N ha^{-1} yr^{-1} and organic N output from 12 to 13 kg N ha^{-1} yr^{-1}. Providing sufficient N would require sowing a legume cover crop on every field every year (Connor, 2008), although legumes remain uncommon in France, in part due to socio-economic factors for farmers (e.g. quality, quantity and price) (Jouan, 2020). In addition, data to model legume cover crops at the national scale was, to our knowledge, not available. Other practices can be considered to increase organic crop yields, such as improving legume crop management, recycling N from organic wastes (e.g. food, human excreta) and increasing the NUE of cropland (Muller et al., 2017; Barbieri et al., 2021; Agora Agriculture, 2024). We also assumed that the N provided by legumes in rotation with cereal crops could also increase N self-sufficiency, as the review of Borghino et al. (2024) identified, in which N-fixing species were included in rotations to increase N self-sufficiency.

In the baseline, organic animal production (5.8 kg N ha^{-1} yr^{-1}) was lower by a factor of 2.2 compared to conventional animal production (12.8 kg N ha^{-1} yr^{-1}). In the BAU and HL scenarios, the number of organic livestock (less productive) increased, while the number of conventional livestock (more productive) decreased (Fig. 3b, c); thus, animal production decreased by 10 % and 27 %, respectively. The production of each animal species depends mainly on breeding practices, feed and the NCE. For example, in the HL scenario, while the weighted mean NCE of organic livestock increased from 13.7 % to 18.0 %, which implied a change in the composition of livestock at the national scale, such as more monogastric animals with a higher NCE, organic animal-based human food increased from 5 to only 7 kg N ha^{-1} yr^{-1}, and organic N output increased from 12 to only 13 kg N ha^{-1} yr^{-1}. As organic livestock have longer production cycles and lower growth rates, more feed and land for feed production are required per unit of organic animal product (Treu et al., 2017). For example, organic cows produce less milk per animal (Nicholas et al., 2004; Rosati and Aumaitre, 2004) (ca. 5000 kg yr^{-1}) than conventional cows do (national mean of 7300 kg yr^{-1}) due to more self-sufficient feeding systems that have more grazing and generally use less concentrates (Idele, 2020). Gaudaré et al. (2021) compared the productivity of organic and conventional livestock and found that the former had 12 % lower productivity, with significant differences in feeding strategies. In France, milk production per dairy cow has increased over time (on mostly conventional farms), from 5036 kg yr^{-1} in 1993, to 6765 kg yr^{-1} in 2012 and 7516 kg yr^{-1} in 2022 (Idele, 2023) (Fig. S1). This increase was also predicted in the EU Agora Agriculture (2024) scenario, but not in observed for organic dairy cows (Fig. S1) because developments in livestock genetics and nutrition have been driven mainly by conventional agriculture. Indeed, we thought that productivity per animal may differ between organic and conventional livestock in the long term due to the relatively small genetic, nutritional, technological and intensification improvements in OA, which do not align with the principles and objectives of OA (IFOAM, 2021). However, prospects for improving organic livestock production have been explored (Suresh, 2024), which have highlighted the potential to increase the production (Thornton, 2010) and the efficiency, sustainability and resilience (Gowtham and Jebakumar, 2023) of organic farms, but more productive OA cannot be expected.

4.4. Potential improvements to the development scenarios and modelling of conventional agriculture

Although this study provided insights into the development of OA in France, there was room for improvement, such as considering the use of human excreta and food waste. Currently, use of human excreta is prohibited in OA, and use of food waste is limited because it must come from a closed system and be collected by local authorities for use in OA (Annex II of EU Regulation (2018/848)). However, human excreta (Starck et al., 2024) and food waste (Oelofse et al., 2013) can be a source of N and contribute to a sustainable and circular agriculture. In the ALPHA-national model, human excreta and food waste were included in human waste. If 10 % of human waste is recycled in the HL scenario, organic crop yield increases from 53 to 56 kg N ha^{-1} yr^{-1}, and organic N output increases from 12 to 13 kg N ha^{-1} yr^{-1}. Starck et al. (2024) found that only 10 % of excreted N in France is recycled and used to fertilise cropland. Van den Broek et al. (2024) estimated that with 50 % recycling and use of human excreta, the need for animal manure could decrease by 68 %. However, food waste and human excreta, like animal manure, may contain contaminants such as pharmaceuticals, persistent organic compounds, heavy metals and pathogens. Thus, consumer prejudice, farmer hesitation and strict regulations discourage their use for now (Van den Broek et al., 2024), particularly among organic farmers, who have been reluctant to accept them (Case et al., 2017).

In both scenarios, we made certain simplifications, such as keeping NUE_{crop} constant (65 %) and assuming a linear response curve for N input, which meant that farm practices did not influence NUE of cropland and that crop yield increased linearly as N input to cropland increased. However, the exact weighted mean response curve of crop yield to N input at the national scale should be addressed, especially when crop mixtures change. Chmelíková et al. (2021) observed high variability in this response curve in farm experiments in Germany, while Billen et al. (2021), based on relations between fertilisation and yield in several countries, highlighted that this response curve is hyperbolic and hence crop yield increases less as N input increases. The ALPHA-national model would be improved by calibrating this response curve for each crop category.

In the current calibration, organic temporary grasslands (196,000 ha, which provided 6 kt N from BNF), some organic artificial grasslands (179,191 ha, 22 kt N) and organic permanent grasslands (999,000 ha, 15 kt N) were grouped into the grassland sub-system. Doing so assumed that some of the N fixed in temporary and artificial grasslands returned to croplands via livestock manure. In addition, some forage (i.e. legume-grass mixture) (145,000 ha, 13 kt N from BNF) was allocated directly to cropland rotations. This approach may have slightly overestimated the proportion of BNF routed through livestock and underestimated direct fertility transfers in crop rotations without livestock. At the national scale, the degree to which temporary grasslands form part of non-livestock-vs. livestock-based systems remains uncertain. However, a regional comparison (Fig. S2) suggests a proportional relation between the number of dairy cattle and temporary grassland area. This relation supports our assumption, especially as 41 % of temporary grasslands of OA in France were located in the Brittany and Pays de la Loire regions, which together host 42 % of France's organic dairy cattle herd. Further analysis at finer spatial scales would help refine the calibration by identifying local practices of temporary grassland integration and the extent to which they are related to livestock.

The sensitivity analysis highlighted that increasing the BNF rate of legumes from 150 to 200 kg N ha^{-1} yr^{-1} in organic and conventional grasslands, was an effective way to provide additional N inputs. The BNF rate greatly influenced model predictions and thus the conclusions, but the legume BNF rate remains uncertain, especially at a macro scale, and difficult to verify in the literature. According to Anglade et al. (2015), mean BNF at the farm scale in France of lucerne and red clover (465 $\pm$ 102 and 252 $\pm$ 100 kg N ha^{-1} yr^{-1}, respectively) were higher than the weighted mean BNF rate used in the present study. This uncertainty highlights the need for more precise monitoring of BNF rates of legumes in OA, along with their agricultural practices, at French and European scales.

Another improvement was to decrease the uncertainty in modelling conventional agriculture. In fact, data on the organic and entire agricultural systems are available, but data on only the conventional system were not. Few studies have calibrated N flows for the entire French agricultural system, and data remain uncertain and vary greatly among studies (Billen et al., 2018; Einarsson et al., 2021; FAOSTAT, 2024a) (Table S17). For example, how feed is allocated among animal species depends on how feed-supply data from multiple sources at the national scale are reconciled (Xu et al., 2021). There were no data on the total amount of livestock feed. However, cropland production and crop residues (Sailley et al., 2021; Agreste, 2024d), grassland production (only some of which was consumed by animals) (Agreste, 2024d), forage production (Agreste, 2024d) and feed imports (FAOSTAT, 2024c) can be collected from datasets and were considered credible. Conversely, crop feed depends on the percentage of crops used for animals (α_{crop}), and data on it at the national scale are relatively less reliable. In the HL scenario, if the percentage of conventional crop production used for animal feed increases from 48 % to 80 %, conventional animal-based human food increases from 10 to 14 kg N ha^{-1} yr^{-1} and conventional crop yield increases from 102 to 114 kg N ha^{-1} yr^{-1}. Increasing the percentage of crop production used for animal feed could increase livestock production, but doing so would increase feed-food competition (Van Zanten et al., 2018).

5. Conclusion

This study integrated characterisation of nitrogen inputs, transformation, and outputs for organic and conventional agricultural systems in France, highlighting key variables associated with livestock that drive both productivity and nutrient functioning. The results provide valuable insights into trade-offs among the expansion of organic agriculture, trends in organic and conventional livestock between ruminants and monogastric animals, nitrogen self-sufficiency and animal products in the diet of the French population. Notably, the scenarios indicate that achieving 25 % of agricultural land under organic agriculture by 2030 will require compromise, as more organic livestock and the prohibition of the use of conventional manure in organic agriculture decreases nitrogen losses but may also decrease food production. In addition, scenarios indicated that if France wants to achieve 25 % of agricultural land under organic agriculture without externalising negative environmental impacts to other countries by importing food, its population needs to decrease consumption of animal products (i.e. by 5 % and 30 % in the BAU and HL scenario, respectively) and thus decrease livestock numbers. Furthermore, the recent decrease in 2022 in the consumption of organic animal products in France is worrying in a context in which consumption of animal products is still increasing and organic agriculture is being promoted. The biophysical analysis demonstrated the key contribution of livestock numbers to the expansion of organic agriculture, but further analysis is required, such as considering changes (e.g. in human diets, farming practices, land use) and economic impacts (e.g. increased food prices). We emphasised that structural changes in organic and conventional crop rotations and livestock can vary among regions, and that national data can mask sub-national diversity; thus, local characteristics and farmers' perceptions need to be considered to produce the most realistic scenarios. Ultimately, this study demonstrates the potential of an integrated modelling framework that opens up possibilities in the context of an agricultural transition in which conventional and more agroecological systems will likely coexist.

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, Supervision. **Joël Aubin:** Writing – review & editing, Supervision. **Souhil Harchaoui:** Writing – review & editing, Supervision, Conceptualization.

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Declaration of competing interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104527.

Data availability

Data will be made available on request.

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