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Challenges and opportunities for improving circularity in the poultry meat and egg sector: the case of France

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Abstract

Poultry is the fastest growing livestock sector worldwide, but it remains underrepresented in studies of crop-livestock integration and circular agricultural systems. This study examined the concept of circularity applied to the poultry supply chain by analyzing nitrogen (N) flows at the national scale for France. Our results show that N-use efficiency of the poultry sector increased from 39% in 1990 to 44% in 2020. In contrast, N self-sufficiency barely changed at 10%, and imports of poultry products increased sixfold. Of the total annual input of 376 kt N, 20% becomes food, 24% is recycled, and 56% is lost to the environment. We explore two pathways to increase circularity: (i) increasing N-use efficiency at each step of the supply chain as well as the percentage of manure N transferred to crop production and by-products used from slaughterhouse and processing industries and (ii) changing feed rations by using more biowaste streams.

29

30 **Highlights**

- 31 • Circularity was characterized by N-use efficiency, loss rate, self-sufficiency, and
32 recycling rate
- 33 • 24% of total N input was recycled, of which 70% was in transferred manure and 30%
34 in recovered slaughterhouse and processing by-products
- 35 • Feed production required 1.4 million ha of farmland, of which 25% lay outside France
- 36 • Poultry-product imports increased sixfold from 1990 to 2020

37

38 **Keywords:** circularity, poultry, integrated crop-livestock systems, nitrogen, land
39 requirements

40

41 **1. Introduction**

42 Livestock production plays a critical role in the food supply and food security. Livestock
43 production systems provide high-quality protein and essential nutrients for humans. Globally,
44 40% of protein and 19% of calories for human consumption come from animal-based food
45 (FAOSTAT, 2022). However, livestock production has significant environmental impacts
46 (Steinfeld et al., 2006), including pollution, land use, water use, climate change, and loss of
47 biodiversity. On a dry matter (DM) basis, feed comprises 60% of the total biomass of food
48 and feed (Mottet et al., 2017) and contributes greatly to the environmental impacts of
49 livestock (Wilfart et al., 2016). Feed production uses ca. 40% of global arable land (Mottet et
50 al., 2017) and more than 41% of all water used in agriculture (Heinke et al., 2020). Production
51 of animal-based food comprises 57% of greenhouse gas emissions in food systems (Xu et al.,
52 2021). Recent analysis highlights that livestock supply chains are a major source of nitrogen

(N) emissions, contributing ca. one-third of global anthropogenic emissions (Uwizeye et al., 2020). The geographic decoupling of livestock and crop systems, associated with specialization of agricultural systems, is currently the main driver behind changes in the biogeochemical cycles of N (Galloway et al., 2003; Sutton et al., 2013), phosphorus (Cordell and White, 2014; Nesme et al., 2015), and carbon (Steinfeld and Wassenaar, 2007). Globally, the consumption of animal protein has more than quadrupled from 1961 to the present (FAOSTAT, 2022) and is expected to increase by 14% by 2030 (OECD, 2021). The challenge in future decades is to meet this increasing demand for animal-based foods while also reducing environmental impacts of livestock production.

Integrated crop-livestock systems (ICLS) provide sustainable strategy for livestock production that can meet these environmental challenges (Ryschawy et al., 2014; Schut et al., 2021). ICLS combines crop and livestock production on the same farm or group of farms to improve soil fertility and nutrient cycling by promoting synergies and complementarities between crop and livestock systems. Several studies explored the driving forces for and barriers to implementing ICLS at the farm scale (Bonaudo et al., 2014; Martel, 2017; Moraine et al., 2014) and, more recently, at the territorial scale (Asai et al., 2018; Garrett et al., 2020; Moraine et al., 2019). These studies identified environmental (Lemaire et al., 2014; Martin et al., 2016; Ryschawy et al., 2018) and economic advantages (Russelle et al., 2007; Wilkins, 2008) of ICLS over specialized systems. Similarly, a wider concept of a circular economy has been developed to address sustainability issues in agri-food systems by focusing on biophysical flows (Muscat et al., 2021) to reconnect crop and livestock production as well as other components of these systems, such as food and feed processing and waste management (Wang et al., 2021). Within this framework, livestock can recycle by-products and biomass into food and manure and then restore its critical role in closing biogeochemical flows (van Selm et al., 2022; Van Zanten et al., 2019).

However, among livestock species, ICLS and circular agriculture of monogastric species, especially poultry, have been studied much less than those of ruminants (Garrett et al., 2017) (see mini-review in Supplementary Information, Fig. S1). This is paradoxical from an historical perspective, since in preindustrial agriculture, monogastric species served mainly as recyclers or scavengers of low-quality feed, such as agricultural waste, leftovers, and forage (Vaarst et al., 2004) on the farm and contributed little to the total amount of animal protein produced. For instance, production data for poultry were not reported in agricultural statistics in France until the late 1960s (Diry, 1985). In contrast, the modern poultry sector is specialized and supported by high-quality nutrient feed. Poultry is a highly efficient protein producer within the livestock sector (Dourmad and Méda, 2021; Smil, 2000) and provides 26% of all animal products worldwide. Globally, the amount of protein in poultry meat and eggs has increased ninefold from 1961 to the present, and in the next decade, poultry consumption will comprise more than half of the world's growth in meat consumption (OECD-FAO, 2022). Recent studies at the national scale (Bai et al., 2016) and global scale (Liu et al., 2017; Uwizeye et al., 2020) have developed models to assess nutrient flows along the entire chain of livestock production systems. However, there is no integrated framework that quantifies all nutrient flows at each step of the supply chain and defines circularity for a specific livestock category such as poultry. To date, only De Boer *et al.* (2000) have examined N flows of the poultry sector at the national scale, for the Netherlands. In addition, few studies have considered nutrient flows associated with the international trade of feed and livestock products (Chatzimpiros and Barles, 2013), but doing so is critical in order to examine the potential to mitigate nutrient losses. Addressing this gap is crucial to provide pathways to sustainable agricultural systems and to understand how poultry convert feed into meat or eggs and play a role in the circularity of nutrients by returning feed and manure back to the soil.

This study examined circularity for the poultry meat and egg sector by analyzing N flows at the national scale for the past 30 years and discusses potential pathways for improving circularity. We use France, the third-largest producer of poultry meat and second-largest egg producer in Europe, as a reference case; however, the generic approach can be applied to any country.

2. Materials and methods

2.1. Overview of the poultry supply sector in France

The French poultry sector produces 1.81 Mt carcass-weight equivalent (cwe) of poultry and 0.84 Mt of eggs annually for domestic consumption and exports (Agreste, 2022a). France currently has ca. 297 million head of poultry, which represent 18% of all livestock head in France. The layer sector represents 46 million laying hens that produce eggs for consumption and 36 million hatching hens and pullets. Broiler production is the largest subsector of the poultry meat supply chain (63%, with 1.1 Mt cwe), followed by turkey (20%) and duck (7%) (Supplementary Fig. S2). The remaining production includes spent laying hens, guinea fowl, and geese (Agreste, 2022a). A total of 52% of French broiler farms are specialized. Poultry meat and eggs are produced mainly in western France, with 60% of the national poultry population in Brittany and Pays de la Loire (Fig. 1a). This sector is supported by an increase in national demand, with poultry meat representing 31% of total per capita meat consumption in 2020 (Agreste, 2022b). Unlike other meat consumption, French per capita consumption of all poultry meat increased by 25% over the past 30 years (Fig. 1b), reaching 29 kg cwe per capita per year and replacing beef and pork (Agreste, 2022b). In contrast, national per capita egg consumption decreased by 21% over the same period. Poultry production in France is

integrated, since farmers have a contractual relationship (Magdelaine et al., 2015) with a production organization or agricultural cooperative. For this strategy, the production organization provides feed and chicks to farmers, who are expected to fatten the poultry or produce eggs and are responsible for waste management.

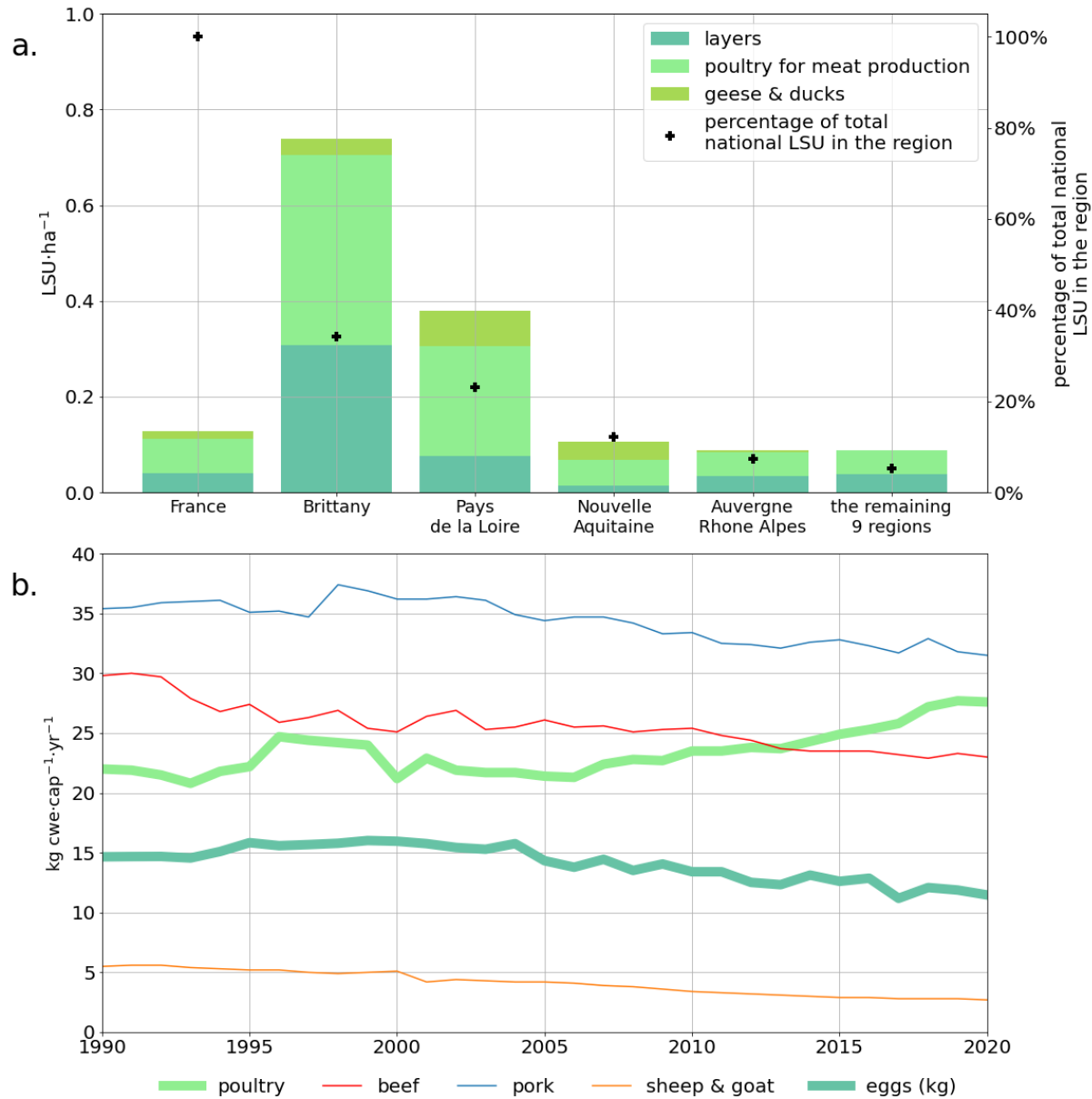


Fig. 1. Overview of the French poultry sector. a. Livestock unit (LSU) density per ha of agricultural land for France and the main administrative regions (left axis) and their respective percentages of total national LSU (right axis) in 2020. b. National per capita meat and egg consumption in kg carcass-weight equivalent (cwe) per year from 1990 to 2020.

2.2. System boundaries

The system under study was the poultry supply chain in metropolitan France from 1990 to 2020. In this study, poultry included three categories: layers, poultry for meat production (including broilers, turkeys and guinea fowls), and geese and ducks (Supplementary Table S1). The system boundaries included four stages of the supply chain: feed production (domestic and foreign), livestock production, manure management, and animal slaughtering and processing. Retail and distribution were not included. The analysis was based on data from French annual agricultural statistics (Agreste, 2022a), national inventory emission data (CITEPA, 2022, 2020a, 2020b), and statistical databases for international trade (Agreste, 2022a; FAOSTAT, 2022). All assumptions and data sources are summarized in Supplementary Tables S1-S3.

2.3. Nitrogen flows and budget

The methods used to analyze N flows (Fig. 2) in the national poultry supply chain were adapted from the framework developed by Uwizeye *et al.* (2016). We determined an N budget for each stage in the poultry supply chain. National statistics (Agreste, 2022a) provided domestic poultry production data for carcass weight and the number of eggs produced. For each poultry production category, the percentage of carcass weight in animal live weight (LW) (dressing percentage), the N content of domestic live animals and eggs, and the percentage of human-edible protein in LW were compiled from different sources (ITAVI, 2013; Laisse *et al.*, 2019; Le Noë *et al.*, 2017; USDA, 1992) (Table 1). These parameters, which we assumed remained constant over the period, allowed us to estimate the distribution between human-edible (meat and offal) and non-human-edible products (bones, skin, head, feet, and other removed parts) after slaughtering and processing (Le Noë *et al.*, 2017).

Table 1. Coefficients used to calculate feed and animal production: the N content in live animals or eggs, percentage of carcass weight in animal live weight (dressing percentage), percentage of human-edible protein in live weight, N excretion factors, and feed ration for each poultry category (CITEPA, 2020a, 2020b; ITAVI, 2013; Laisse et al., 2019; Le Noë et al., 2017; USDA, 1992). Except for CITEPA (2020b) assumptions of annual N excretion factors, all other coefficients were assumed to be constant from 1990 to 2020. The N excretion factor for layers is the mean N-excretion factor weighted by flock size for laying hens that produce eggs for consumption, hatching hens, and pullets.

	Broilers	Turkeys	Guinea fowls	Layers	Geese	Ducks
N content in live animals or eggs ¹ (%)	2.89	3.58	3.84	laying hens: 2.08 eggs: 1.79	2.88	2.80
Dressing percentage ² (%)	70	80	68	55	65	70
Human-edible N in live weight after slaughtering and processing ³ (%)	57	50	50	55	50	50
Excretion factor ⁴ (kg N·animal ⁻¹ ·yr ⁻¹)	0.33	1.03	0.26	0.60	1.35	0.74
Feed rations (% of total dry matter)						
Cereals	65	65	65	67	75	75
Oilseed cakes	24	24	24	25	12	12
Oilseeds	2	2	2	1	9	9

Cereal by-products	3	3	3	3	1	1
Other products ⁵	6	6	6	5	4	4

¹N content in live animals is based on ITAVI (2013) and N content for eggs on Le Noë *et al.* (2017)

²Dressing percentages for broilers and layers are based on Laisse *et al.* (2019), on USDA *et al.* (1992)

for turkeys and authors' estimates for the remaining poultry categories ³Percentage of human-edible N

in live weight after slaughtering and processing for broiler is based on Laisse *et al.* (2019) and authors'

estimates for the remaining poultry categories . ⁴Excretion factors are for the year 2018 which is the

last year provided by CITEPA (2020b). Excretion factors are assumed constant for 2019 and 2020.

⁵Other products include other agri-food by-products, additives, and mineral salts.

We assumed that percentage of N in non-human-edible products that is recovered as by-

products from slaughterhouses and processing (N_{byprod} , kt N·yr⁻¹) was 60% and remained

constant over the period. The remaining 40% was slaughterhouse waste and food loss.

National statistics do not provide enough details to estimate the N in by-products used for pet

food, compost, and animal feed (Réséda, 2017). Similarly, for the egg supply, they do not

include waste (i.e. broken eggs) or the use of eggshells for compost or other agri-food

purposes. The total N produced in the poultry sector equaled the sum of N content in all live

poultry categories and egg production. Import and export data for live animals, meat, and eggs

(Agreste, 2022a) were converted into their N content (Lassaletta *et al.*, 2014). Total annual

excreted N (N_{manure} , kt N·yr⁻¹) equaled the sum of N excreted by all poultry categories (Eq.

1):

$$N_{manure} = \sum_i Heads_i \times \frac{F_i^{exc}}{1000} \quad (\text{eq. 1})$$

where i is the poultry category, $Heads_i$ are the numbers of animals per year and F_i^{exc}

(kgN·animal⁻¹·yr⁻¹) are N excretion factors per category (Table 1).

The fate of excreted N in buildings, on runs, during storage, and in manure transferred to crop production, as well as N loss, was calculated using a detailed annual N-budget analysis from 1990 to 2018 (CITEPA, 2020b) that we supplemented for 2019 and 2020. Manure transferred to crop production was divided between that transferred to produce poultry feed ($N_{poultry}^{manure}$, kt N·yr⁻¹ as internal flow) or non-poultry feed ($N_{non-poultry}^{manure}$, kt N·yr⁻¹). We assumed that the distribution of manure applied to poultry feed crops (N_{inputs}^{manure} , kt N·yr⁻¹) between poultry manure ($N_{poultry}^{manure}$) and manure for other livestock categories (N_{other}^{manure} , kt N·yr⁻¹) was identical to the average distribution of manure applied to all crops harvested in France and reported by CITEPA (2020a, 2020b). In the livestock-production stage, N-retention efficiency (%) equaled the N content in live animals and eggs divided by total feed N, times 100. In the manure management stage, the manure N recovery rate (%) equaled the N transferred to cropland after N losses in buildings, storage and spreading (but not N transformation in the soil) divided by the total N excreted in buildings (excluding manure transferred on runs), times 100. After the slaughtering and processing stage, the conversion efficiency of edible-product N (%) was calculated as the product of N-retention efficiency and the percentage of human-edible N in LW.

Agricultural statistics do not include information on feed per livestock category (Harchaoui and Chatzimpiros, 2017). The composition of feed rations was reconstructed from the recent analysis of Sailley *et al.* (2022), who covered all livestock categories in France for 2015 (Table 1). We calculated total feed N as the sum of total N produced in the poultry sector and total excreted N. Feed ingredients were divided into five categories: cereals, oilseed cakes, oilseed grains, cereal by-products, and other products (other agri-food by-products, animal feed additives, and mineral salts). The origin of feed ingredients was determined from domestic availability balances (Harchaoui and Chatzimpiros, 2017; Agreste, 2000, 2021) for each category at the national level (Agreste, 2022b; FAOSTAT, 2022), except for the other

products due to lack of reported data. We assumed that feed rations remained constant from 1990 to 2020 (Table 1) for each poultry category. The percentages of cereals and oilseed cakes likely varied, but there were not enough specific data to consider these differences over time (Supplementary Table S2).

The total annual N fertilization inputs required to produce poultry feed in France ($N_{inputs}^{dom,tot}$, kt N·yr⁻¹) were calculated assuming a mean national crop N-use efficiency (NUE_{crop} , %) reported in a recent study (Einarsson et al., 2021), which we supplemented for 2020 and expressed as (Eq. 2):

$$N_{inputs}^{dom,tot} = BNF + N_{atm} + N_{ind} + N_{inputs}^{manure} \quad (\text{eq. 2})$$

where BNF is biological N fixation, N_{atm} is atmospheric deposition, N_{ind} are industrial N fertilizers and N_{inputs}^{manure} are manure N spreading inputs to poultry feed in France. We assumed the same levels of crop fertilization at the national scale reported in the same study (Einarsson et al., 2021). The external N fertilization inputs required to produce feed in France (N_{inputs}^{dom} , kt N·yr⁻¹) were calculated by subtracting the internal manure flows from the poultry sector from $N_{inputs}^{dom,tot}$: $N_{inputs}^{dom} = N_{inputs}^{dom,tot} - N_{poultry}^{manure}$. The N fertilization inputs (N_{inputs}^{for} , kt N·yr⁻¹) required to produce imported feed (mainly soybean cake and grain) were calculated based on foreign crop N-use efficiency (NUE_{crop}^{for}). Since a mean of 70% of soybean cake imported into France from 1990 to 2020 came from Brazil (FAOSTAT, 2022), we simplified estimation of N_{inputs}^{for} by assuming that all feed was imported from Brazil and used the latter's historical national median NUE_{crop}^{for} (1990-2015) (X. Zhang et al., 2021). N flows associated with the straw used in litter and crop residues returned to the soil were excluded, due to a lack of data. We assumed that parent animals were not including in national statistics used and their production was not included in this study. The equations used to model N flow are presented in Supplementary Information (Table S3).

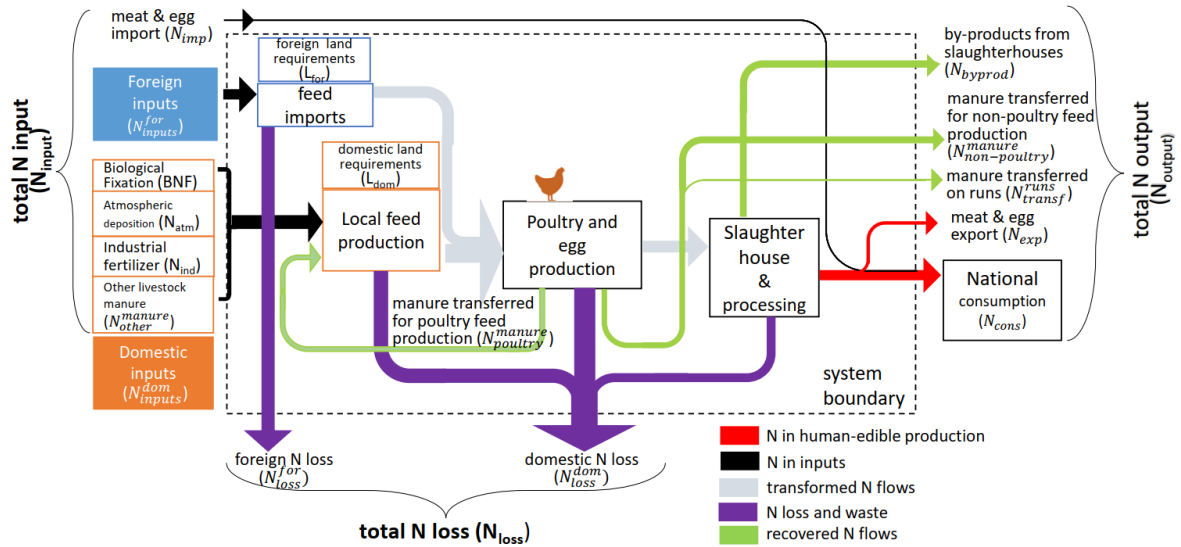


Fig. 2. Nitrogen flow (N) diagram of the poultry supply chain system modeled. All N flows are in absolute value ($kt\ N \cdot yr^{-1}$). Foreign and domestic land requirements for feed production (L_{for} and L_{dom} , respectively) are agricultural areas (ha).

2.4. Land requirements

Land requirements equaled the sum of the agricultural area required to feed poultry (Harchaoui and Chatzimpiros, 2017). We excluded the land required to feed the animals used to produce imported meat and egg products. The direct land occupation of livestock buildings, which is currently ca. 2 490 ha in France (ITAVI, 2013), was considered negligible and thus excluded. For each year, land requirements were calculated by dividing the quantity of each feed ingredient by the crop yield required to produce it (FAOSTAT, 2022). For oilseed cakes, the land requirement for oilseed grain was divided between the co-products (oil and cake) of grain processing using an economic allocation factor, in accordance with EcoAlim recommendations (Wilfart et al., 2016). Land requirements were divided between domestic (L_{dom} , ha) and foreign land (L_{for} , ha) based on the availability of each feed ingredient at the national scale (Harchaoui and Chatzimpiros, 2017).

258

259 2.5.Circularity

260 There is no commonly accepted definition of circularity. In the past decade, circularity has
 261 gained prominence in national economic policies, such as strategies of member states of the
 262 European Union (EU) for a circular economy. However, circularity is not a new concept,
 263 since it was already mentioned by Odum (1989) when describing matter and nutrient flows in
 264 ecological systems. According to Kleinpeter *et al.* (2023), “circularity reflects how nutrient
 265 cycles are closed”. Circularity approaches must go beyond increasing the efficiency of
 266 nutrient conversion along the chain of agricultural production systems (Muscat et al., 2021).
 267 Here, we examined circularity for the poultry sector (Fig. 2) as a means to achieve the
 268 following simultaneously: (i) higher resource-use efficiency, (ii) lower environmental
 269 impacts, (iii) lower dependence on external inputs, and (iv) higher reuse of flows of matter
 270 between crop and livestock systems. We did not, however, consider the circularity dimensions
 271 of feed-food competition or the energy cost of poultry production. Accordingly, we defined
 272 four N indicators for circularity: (i) N-use efficiency of the poultry sector ($NUE_{sector, \%}$), (ii)
 273 domestic N-loss rate ($R_{loss, \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}}$), (iii) N-self-sufficiency ($N_{self-sufficiency}$) (Harchaoui
 274 and Chatzimpiros, 2018), and (iv) N recycling rate ($N_{recycling, \%}$) (Eq. 3-6):

$$275 \quad NUE_{sector} (\%) = \frac{N_{output}}{N_{input}} \quad (\text{eq. 3})$$

$$276 \quad R_{loss} (\text{kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}) = \frac{N_{loss}^{dom}}{L_{dom}} \quad (\text{eq. 4})$$

$$277 \quad N_{self-sufficiency} (\%) = \frac{(N_{atm} + BNF)}{N_{input}} \quad (\text{eq. 5})$$

$$278 \quad N_{recycling} (\%) = \frac{(N_{by-prod} + N_{non-poultry}^{manure} + N_{poultry}^{manure})}{N_{input}} \quad (\text{eq. 6})$$

279 where

- total N input (N_{input} , kt N·yr⁻¹) equals the sum of all N inputs of fertilizers for domestic (N_{inputs}^{dom}) and foreign feed ingredients (N_{inputs}^{for}), oilseed cake, and grain imports; and international imports of meat, eggs, and live animals
- total N output (N_{output} , kt N·yr⁻¹) equals the sum of N in meat and eggs for national consumption; slaughterhouse by-products used in other agri-food sectors; manure transferred for non-poultry-feed crop production; and international exports of meat, eggs, and live animals
- domestic N loss (N_{loss}^{dom} , kt N·yr⁻¹) is the sum of all loss and waste occurring domestically, including N loss from domestic feed-crop production, manure management, and waste from slaughterhouses and processing
- domestic land requirements (L_{dom} , ha) equal the sum of all land used domestically to produce feed for the poultry sector

2.6. Sensitivity and uncertainty analysis

A sensitivity analysis was conducted for the model's main input parameters to understand their influence on each of the four circular indicators (Supplementary Table S4). Uncertainty in estimates of outputs was assessed in two steps. First, we assigned uncertainty, expressed as a coefficient of variation (CV, %) (Cameira et al., 2019), to each key input parameter based on the literature and personal judgement (Supplementary Table S5). The CV of these parameters were estimated to range from 2% (e.g. agricultural statistical data) to 20% (e.g. percentage of human-edible N in LW). Second, we performed 10,000 Monte-Carlo simulations for 2020 (using a python software) that varied all parameters simultaneously, assuming that each parameter followed a normal distribution and that no parameters were correlated, to assess the influence of parameters on model estimates (Supplementary Table S6).

3. Results and discussion

3.1. Nitrogen flows in the poultry supply chain in France

A simplified diagram of N flows in the French poultry supply chain distinguishes steps of N transformation for 2020 (Fig.3. Production of human-edible poultry products currently represents ca. 58 kt N per year (70% in meat and 30% in eggs). It comprises 18% of all animal-protein production in France, including meat and milk (FAOSTAT, 2022). Overall N-retention efficiency is estimated at 40%, which is equal to that estimated for the Chinese poultry sector (Bai et al., 2016). Individual N-retention efficiencies are 49% for poultry for meat production, 28% for egg production, and 38% for goose and duck production, which are, however, lower than estimates of 55% and 32% in Germany for broiler and egg production, respectively (Groenestein et al., 2019). These differences can be explained by the larger percentage of alternative and intermediate-growth-rate strains produced under official identification labels (e.g. Label Rouge, organic) in France (nearly 15%) than in Germany. Indeed, the feed-conversion ratio, which expresses the efficiency of converting feed into LW, can be as high as 3.08 kg feed/kg LW for Label Rouge broilers, compared to 1.64 kg feed/kg LW for standard broilers in France (ITAVI, 2020). Intermediate-growth-rate strains have lower N-use efficiency than standard broilers but higher sensorial quality (Chan et al., 2022) and animal welfare standards.

Poultry feed comprises 230 kt N per year, mainly concentrates, divided among poultry for meat production (60%), layers (30%), and geese and ducks (10%). This total feed estimate lies at the lower end of the 20% confidence interval of the estimate of Saille *et al.* (2022). Imported oilseed grains and cakes comprise 44% of the N content in poultry feed (101 kt N). Soybean cake comprises 75% of total oilseed cakes, while sunflower cake and rapeseed cake comprise the remaining 25%. Nearly 96% of soybean cake used for feed in France was imported in 2020 (Agreste, 2021). Overall, 60% of soybean cake imports came from Brazil,

25% from other European countries, and 15% from other countries (mainly Argentina and marginally India) in that year. Foreign N inputs required for feed imports (179 kt N) are higher than domestic N inputs for local feed (169 kt N) due to the difference in crop N-use efficiency between France ($NUE_{crop} = 68\%$) and foreign exporter countries such as Brazil ($NUE_{crop}^{for} = 55\%$). The poultry sector also depends indirectly on N upstream of feed production in the form of industrial N fertilizers, estimated at 98 kt N, which represents 6% of industrial N fertilizers used nationally in agriculture.

N losses along the supply chain are estimated at 210 kt N per year (Fig. 3), distributed among the stages of foreign feed production (37%), domestic feed production (26%), manure management (30%), and slaughtering and processing (7%). Our estimate of 137 kt of total N excreted is 8% lower than that in the Food and Agriculture Organization database due to different assumptions about N excretion factors. N in poultry waste is 40% higher than that in the industrial N fertilizer used to produce poultry feed at the national level (Fig. 3). We estimate that 54% of total excreted N is spread on crops in 2020; which is slightly less than Loyon's (2018) estimate of 55% in 2010, when there was less free-range production. Our calculations estimate that 62 kt N of poultry manure is transferred and spread on arable crops. Approximately 10% of this manure N is internally recycled to fertilize crops for poultry feed, while the remaining 90% is used to fertilize other crops (Fig. 3).

In the slaughtering and processing stage, we estimate that ca. 54% of N in animal LW is human-edible. The remaining non-human-edible N is in poultry by-products, used mainly for pet food, animal feed, and compost, and in N losses. The split between losses and by-products is uncertain due to a lack of statistical data. The N-conversion efficiency of edible products is nearly 25%. This percentage is consistent with the 22.5% estimated for the USA (Shepon et al., 2016). The supply chain is also connected to international trade, with 17 kt N in imports and 13 kt N in exports, typical of the poultry sector in Europe, which also contributes to

decoupling of nutrient flows between countries. In addition, imports and exports expressed in N conceal the fact that the kinds of products exchanged differ, with cuts of heavy chickens (ca. 2.5 kg LW at slaughter) imported and light chickens (1.4 kg LW at slaughter) exported. N self-sufficiency of poultry sector is estimated at 10% (Table 2) and reflects the high dependence on both industrial N fertilizers and foreign N inputs for feed imports. $N_{\text{self-sufficiency}}$ can be compared to the overall N self-sufficiency of agriculture in France, estimated at 19% (Harchaoui and Chatzimpiros, 2018). We estimate that the N recycling rate is nearly 23%. Interestingly, flows of recycled N (88 kt N), split between 23% in by-products from slaughterhouses and 77% in transferred manure, are larger than the final N consumption (61 kt N). Overall, our calculations indicate that the poultry supply chain is 44% N efficient (Fig. 3) with total annual input of 376 kt N (Fig. 2). Improving efficiency in each step of the chain would decrease N emissions and exposure to risks associated with importing industrial N fertilizer and soybeans, such as supply disruption or price volatility. The sensitivity analysis (Supplementary Table S4) highlights that NUE_{crop} and the manure N recovery rate influenced the four circularity indicators the most. In addition, we estimate that R_{loss} and $N_{\text{recycling}}$ had the highest uncertainty (17-18%) (Table 2, Supplementary Table S6).

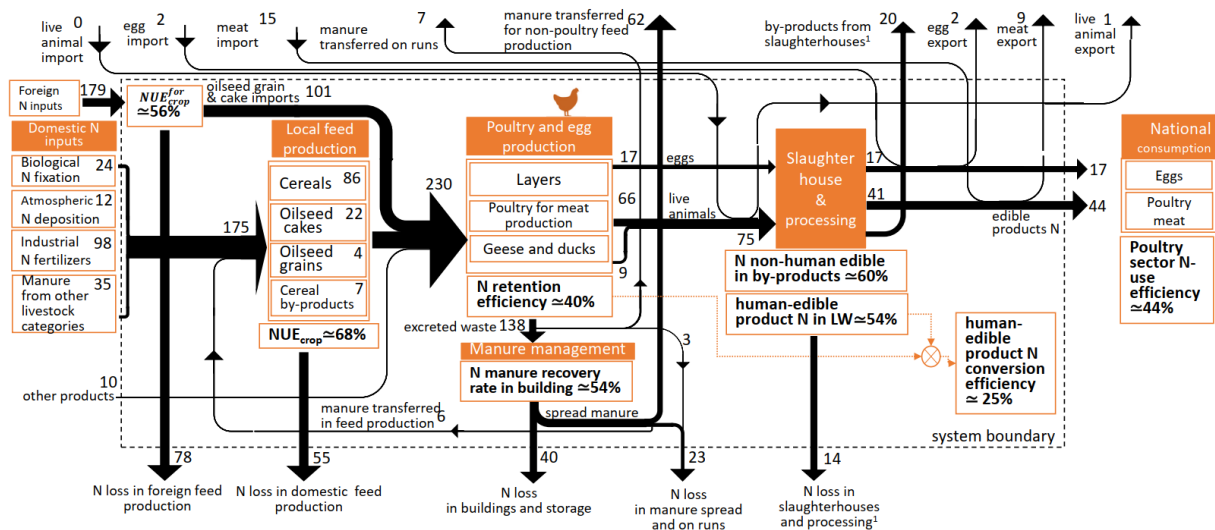


Fig. 3. Simplified diagram of nitrogen (N) flows per year (kt N·yr⁻¹) in the French poultry supply chain in 2020. N-use efficiency is calculated in each step of the supply chain for crop N-use efficiency for feed imported from foreign countries (NUE_{crop}^{for}) or produced domestically (NUE_{crop}), N-retention efficiency, the percentage of N in non-human-edible products that is recovered in by-products, and percentage of human-edible N in live weight (LW). The conversion efficiency of edible-product N equals edible-product N divided by feed N, times 100. N-use efficiency of the poultry sector is estimated across the supply chain defined by the system boundary. ¹Flows associated with slaughterhouse by-products have greater uncertainty. Losses during consumption are not included due to lack of data.

Table 2. Estimates and uncertainty of circularity indicators of the French poultry sector in 2020. Uncertainty is expressed as a coefficient of variation (CV,%).

	Sector N-use	Domestic N-	N self-	N recycling
Circularity	efficiency	loss rate	sufficiency	rate
Abbrev.	NUE_{sector}	R_{loss}	$N_{\text{self-sufficiency}}$	$N_{\text{recycling}}$
Unit	%	$\text{kg N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	%	%
Estimate	44	125	10	24
CV	13	17	8	18

3.2. Trends in nitrogen flows in poultry supply chain from 1990 to 2020

From 1990 to 2020, we estimate that N output increased by 20% to 165 kt N per year after peaking at a 30% increase in 2002 (Fig. 4a). National poultry consumption increased by 27%, while exports decreased by 25%. Over the same period, total N input increased by only 3% (Fig. 4b), due in part to a sixfold increase in meat and egg imports. As a result, the trade balance of the poultry sector in France has decreased over the past 30 years and has been negative since 2016 (Supplementary Fig. S3). While France is a net exporter of live poultry, imported poultry meat comprised more than 36% of national consumption in 2020, compared to less than 7% in 1990. Overall, 70% of these imports come from Poland, Belgium, and Germany, while the rest come from other EU countries (FranceAgriMer, 2021). Total N loss decreased by 15% (Fig. 4c) over the period, driven mainly by an increase in NUE_{crop} in France and, for imported feed, in foreign countries (Fig. 5a). Domestic NUE_{crop} increased from 61% in 1990 to 68% in 2020. However, the NUE_{crop} in France seems to have plateaued at close to 70% in recent decades. The overall N-retention efficiency of poultry and egg products varied in a narrow range from 38 to 43% from 1990 to 2020 at the national scale (Fig. 5b). These latter changes were driven by the genetics and health conditions of the

animals and better animal production practices at the farm level. Nevertheless, the N-retention efficiency has plateaued in recent years and may even decrease due to the increased prevalence of production systems that raise intermediate-growth-rate strains. Improved manure management practices increased the manure N recovery rate by 4 percentage points over the period (i.e. from 50% to 54%) (Fig. 5c). Note that manure excreted on runs currently represents 8% of total N excreted, having nearly doubled over the period. This increase coincides with the increased percentage of laying hens with access to a run, from ca. 16% in 2000 to 50% in 2020. In addition, N-use efficiency of the entire sector increased by only 4 percentage points, and N self-sufficiency remained bound in a narrow range (i.e between 8% and 12%) from 1990 to 2020 (Fig. 5c). The domestic N loss rate decreased by 10% to 125 kg N·ha⁻¹·yr⁻¹ (Fig. 5d). In sum, except for increased imports of poultry products, we identified no major changes in circularity for the poultry sector at the national scale from 1990 to 2020 according to the four indicators (Fig. 5).

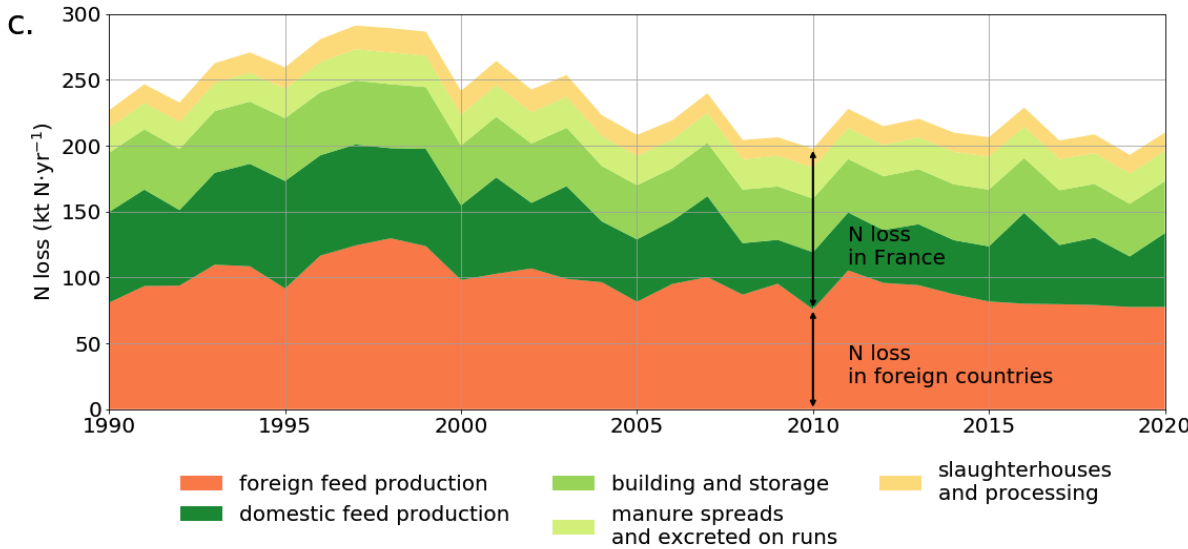
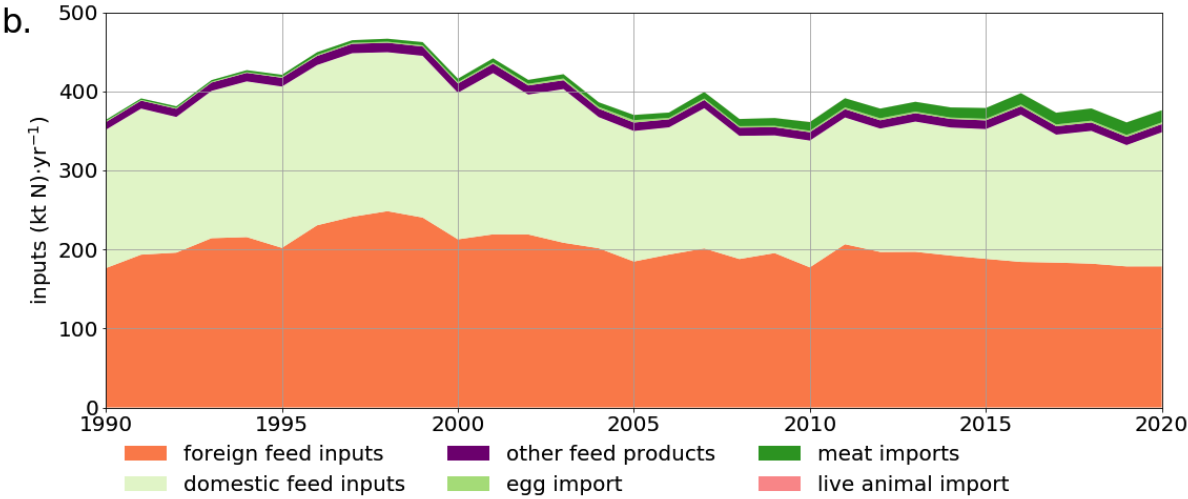
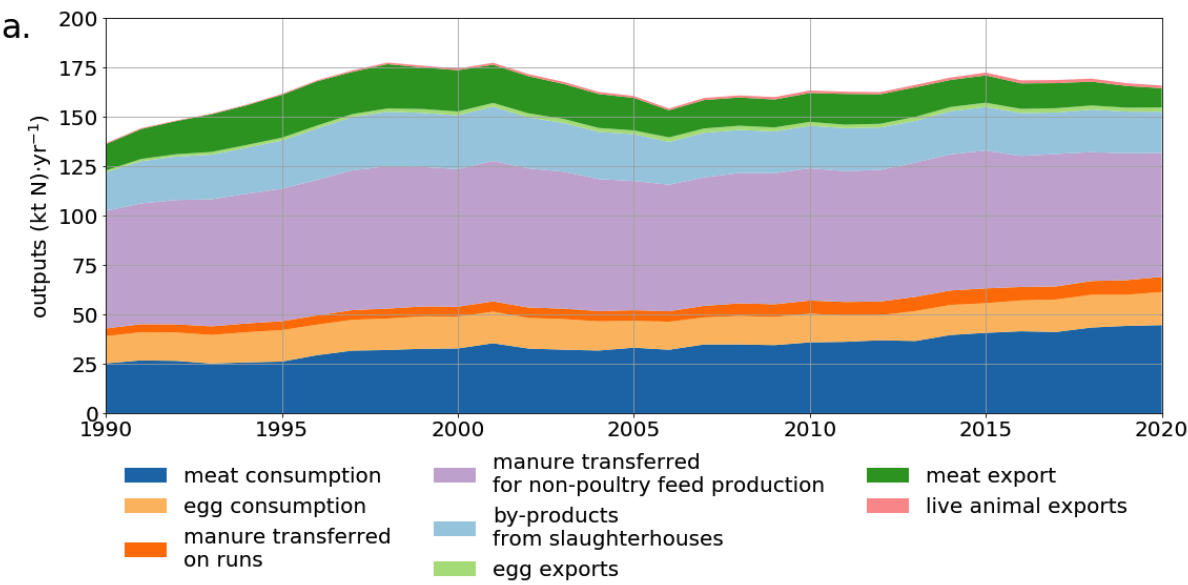


Fig. 4. Annual nitrogen (N) budget (kt N·yr⁻¹) of the French poultry supply chain from 1990 to 2020. a. Total N output. b. Total N input. c. Total N loss.

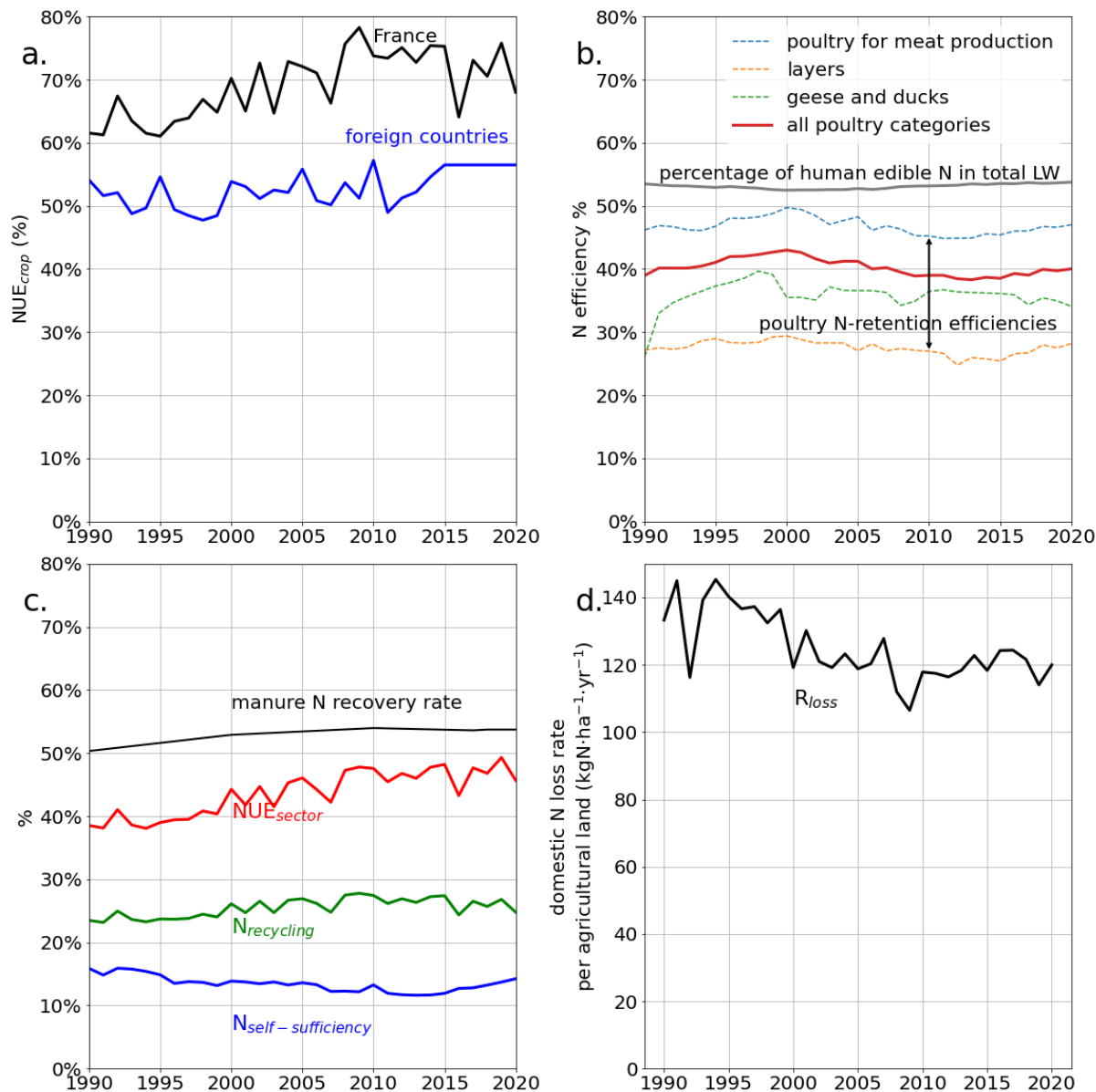


Fig. 5. Crop nitrogen (N)-use efficiency, N-retention efficiency, and N circularity indicators of the French poultry supply chain from 1990 to 2020. a. Crop N-use efficiency in France and foreign countries (Brazil), based on Einarsson *et al.* (2021) and Zhang *et al.* (2021), respectively b. N-retention efficiencies for poultry for meat production, layers, and geese and ducks, and percentage of human-edible N in total live weight. The red line is the weighted mean poultry N-retention efficiency for all poultry categories c. Poultry-sector N-

use efficiency (NUE_{sector}), N self-sufficiency ($N_{\text{self-sufficiency}}$), N recycling ($N_{\text{recycling}}$), and manure N recovery rate d. N-loss rate per ha of agricultural area in France used for feed production (R_{loss}). The four circularity indicators are NUE_{sector} , $N_{\text{self-sufficiency}}$, R_{loss} , and $N_{\text{recycling}}$.

3.3.Land requirements

The land required to produce animal feed is another critical indicator of resource use in the poultry sector (Table 3). We estimated it at 1.4 Mha, compared to 12 Mha of total arable land for cereal and oilseed production in France. This is higher than the 1.27 Mha estimated for broiler and laying hen feed in a previous analysis (Dourmad et al., 2019) based on life cycle assessment that included all livestock categories. The differences are most likely due to different assumptions about the feed rations. Of note, our estimated land requirements are one order of magnitude higher than the current land use of specialized poultry farms in France (0.34 Mha; Agreste, 2022a), highlighting the imbalance between high poultry density and available land for feed. These estimates show that 25% of total poultry land requirements lies outside of France (Table 3) and concerns mainly soybean cake imports. Poultry-sector land requirements in foreign countries (0.34) Mha are 79% higher than the total amount of land used for soybeans in France (0.19 Mha) (Agreste, 2022a).

Table 3. Feed composition and land requirements for poultry production in France in 2020. Feed rations are estimated based on Sailley *et al.* (2022)

Feed ingredient category	Quantity kt at 85% dry matter	N content kt N	Percentage of N imported %	Land requirements		
				Domestic Mha	Foreign Mha	Total Mha
Cereals ¹	5 705	86	0	0.91	0	0.91
Oilseed cakes ²	1 925	119	81	0.07	0.30	0.37
Oilseed grains	236	8	56	0.04	0.04	0.08
Cereal by-products	220	7	0	0.05	NA	0.05
Other products ³	417	10	NA	NA	NA	NA
Total	8 504	230	44	1.07	0.34	1.41

¹Cereals include wheat, barley, and maize. ²Oilseed cakes include soybean, sunflower, and rapeseed cakes. ³Other products include other agri-food by-products, additives, and mineral salts. Land requirements are not applicable (NA) due to a lack of reported data.

3.4. Circularity management options for the poultry sector

Similar to the recent analysis by Kleinpeter *et al.* (2023) applied to a broader agri-food system, we distinguish two main pathways for improving circularity: (1) increasing N-use efficiencies without making large structural changes to the poultry sector and increasing recycling of N flows (business-as-usual, BAU) and (2) potential restructuring of the feed component of the supply chain (RES).

3.4.1. Business-as-usual pathway

In BAU, we assume a 10% increase in NUE_{crop} , the manure N recovery rate, and the percentage of N in non-human-edible products that is recovered in by-products. Note that each driver of efficiency involves different stakeholders, such as domestic and foreign feed producers, poultry farmers, and slaughterhouse managers. We argue that N-retention efficiencies in BAU can no longer be improved at the animal level due to societal expectations for animal welfare and consumer demands for intermediate-growth-rate strains. Feed rations do not change. Compared to current values, BAU increases N efficiency of the sector to 51% and the N recycling rate to 29%, decreases the N-loss rate to $102 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$, but does not influence N self-sufficiency.

BAU requires further improvement of best management practices (Cappelaere et al., 2021; Santonja et al., 2017) to manage and treat manure in livestock buildings and during storage, and advanced spreading practices (e.g. direct or post-treatment) to reduce N loss during the poultry-production stage (Oenema et al., 2007). The latest mitigation and technical measures to reduce N losses are summarized by Hutchings *et al.* (2020). However, financial incentives and legislation for best management practices could be implemented to promote reduction of N losses and integration of poultry and crop systems (Schut et al., 2021). For poultry farmers, improving the manure N recovery rate also reduces the dependence of other sectors on imported fertilizers and economically benefits non-poultry farmers since they can use more manure from poultry farmers. Cropping and poultry systems can be connected more easily if farmers have enough arable land on which to spread excess manure and thus export less of it. BAU would result in fewer poultry farms with no arable land, which currently represent 25% of poultry farms in France (Eurostat, 2022).

Slaughterhouses are another central element of the supply chain, since they collect and process poultry into ready-to-eat products and generate several by-products and types of

waste (Mozhiarasi and Natarajan, 2022). These outputs are classified under EU regulations into three categories (Wilfart et al., 2021): C1 (environmental contaminants, residues of toxic substances, and transmissible spongiform encephalopathy) C2 (the digestive tract, which presents health risks) and C3 (by-products without health risks). C3 products have several uses, such as processed animal protein, animal fats, and pet food. EU regulations have recently re-authorized using poultry-derived processed animal protein in pig feed. In France, one-third of C3 products by mass from all livestock categories currently comes from poultry (Réséda, 2017). C1 and C2 products are destined for agricultural uses and energy production (Lasekan et al., 2013), but the exact use per output category and per livestock category is not widely available. Better knowledge of volumes and uses would help to better assess the potential for recovering by-products from slaughterhouses and processing.

3.4.2. Restructuring pathway

In RES, we assume that we can change feed origins in one of two ways. In the first, we relocate 50% of all imported feed production to France. This option requires increasing current domestic land requirements (1.07 Mha) by at least 20% (1.30 Mha), mainly due to 25% lower yields of soybeans in France than in Brazil. This estimate is optimistic since it assumes that soybean could be harvested easily in France, even though it has no arable land available. Although the area in France on which soybean is grown has increased by more than 70% over the past 30 years, it remains less than 190 000 ha and is used mainly to produce soybeans for human consumption. Any protein crops (e.g. rapeseed, sunflower) or legumes (e.g. lupin) (Pampouille et al., 2021) other than soybeans would likely require even more land due to their lower protein content and yields. This raises questions about the allocation of agricultural land use in France for other livestock categories and competition with production of food for direct human consumption. This result is consistent with a broader analysis of

potential impacts of stopping soybean imports for livestock at the European scale (Karlsson et al., 2021). However, relocation of feed production could work to some extent if coupled with new regulations, economic incentives, or specifications that emphasize qualitative aspects of feed (e.g. origin, GMO-free, non-deforesting). Nevertheless, compared to BAU, we estimate that this option increase N efficiency of the sector to 46%, N self-sufficiency to 15%, and the N recycling rate to 27%, and decreases the N loss rate slightly, to $119 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$.

The second option is to increase flows of biowaste and by-products from the food industry into feed rations, as encouraged by the EU's "Farm to Fork" strategy. This option was not assessed quantitatively due to a lack of large-scale data. The challenge of this option is to maintain high N-retention efficiency while replacing raw ingredients used in feed with novel protein ingredients that do not compete with human consumption. This requires considering the appropriate ratio of protein to calories in livestock diets. RES requires that feed formulations be guided not only by market prices but by the origin, feed-food competition, and environmental impacts of feed ingredients (Garcia-Launay et al., 2018; Wilfart et al., 2016). Insect-fed poultry production could be a partial solution if the insects are raised on non-human-edible plant residues or organic side streams (Huis, 2022). Free-range management could be oriented towards producing feed (e.g. worms, insects, plants) in outdoor runs. Previous studies on experimental farms have shown that a managed run can provide 10% of DM intake (per day) and improve the feed-conversion ratio by 0.08-0.21 depending on the season (Peron, 2019). Another option would be to use manure to produce insects fed to poultry (Čičková et al., 2015; J. Zhang et al., 2021), but it currently has little short-term potential until food industry biowaste and by-product streams are better quantified, and it raises issues about regulation, safety, and animal welfare.

3.5. Challenges and limits of the framework

Although this national-scale framework is a first step in examining circularity of the poultry sector, it has three limitations. Firstly, the choice of indicators and system boundaries to characterize circularity is not universally agreed upon in literature. Unlike the concepts of circularity, whose main principles have converged over the last decade (Atinkut et al., 2020; Muscat et al., 2021; Velasco-Muñoz et al., 2021). Nevertheless, further research to homogenize circularity indicators for the livestock sector would be beneficial to provide insights to policy makers and stakeholders when comparing livestock sectors and monitoring progress over time. The second limitation in our modeling approach is the uncertainty in certain inputs and assumptions. Feed rations are the most difficult data to assess because, in France, there are no national statistics for them by livestock category, let alone over time. In addition, annual flock size and production statistics in France provide information on only 10 aggregate poultry categories but do not report it by production method (e.g. standard vs. alternative). This lack of detail decreases the accuracy of N-loss coefficients in buildings and during storage. Data on slaughter, processing, and distribution flows by livestock category are not available. In a recent analysis of poultry flows in slaughterhouses in Italy, Bux and Amicarelli (2022) recommended bridging this gap by directly surveying large slaughterhouses. A third limitation is that this study does not address the geographic distribution of N indicators (Bai et al., 2022; Nesme et al., 2015). Estimates of N-budget flows are averaged here at the national scale, even though poultry is highly concentrated in only a few regions of France (Fig. 1a). National mean N-loss rates conceal contrasting situations at regional and farm scales. Some farms import or export all of their feed or manure, respectively, while others have greater N self-sufficiency. Reaching N self-sufficiency would require, for instance, changing arable land use and relocating poultry according to available feed sources and the presence of slaughterhouses, processing factories,

and distribution facilities in each region. However, the existing integrated organization of the poultry sector can be an advantage in addressing this challenge at the regional scale. An appropriate solution for transitioning to more circular poultry farming must include consultation with local stakeholders to design systems that are economically viable and tailored to the constraints of the regions and agricultural sectors involved. This means developing quantitative environmental and economic analysis with bottom-up approaches to estimate and adapt quantities of local manure, feed, and animals (Du et al., 2022) based on available land resources.

4. Conclusion

Our study provides an initial assessment of N flows and circularity in the French poultry sector in an historical perspective. It presents insight into changes in circularity over time using four indicators related to N use efficiency, the N loss rate, N recycling rate and N self-sufficiency. According to our results, more than 56% of total N inputs are currently lost and wasted each year requiring the development of poultry sector-wide strategies to increase circularity and thus reduce losses, especially as the demand for poultry products continue to grow. The sector's low N self-sufficiency, due to its dependence on industrial fertilizers and imported feed, may make it vulnerable to price disruption and supply risks. Two scenarios of possible futures were discussed in this study. Business-as-usual yielded only a small increase in circularity related to technical progress, especially the ability to improve the efficiency with which poultry convert feed into human-edible products, appears to be relatively limited. In comparison, restructuring the sector improved circularity more by increasing manure recovery and recycling of slaughterhouse and processing by-products through the supply chain. Additional research from regulatory, safety, logistical and economic perspectives is needed to

581 modify feeding practices to increase the use of biowaste streams. The accuracy of the N-flow
582 approach used in this study should be increased. To address this uncertainty, we emphasize
583 the need for improved data, particularly the quality of national statistics on feed composition
584 and origin, manure management, as well as the fate of by-products streams during slaughter
585 and processing. However, the present study provides a basis for further circularity studies that
586 should be extended to the use of broader resources such as phosphorus and carbon. In
587 addition, energy functioning of the poultry sector is essential in analyzing circularity as any
588 increase of recovery and recycling of nutrients must be achieved by minimizing the use of
589 non-renewable energy.

591 **Declaration of Competing Interest**

592 The authors declare that they have no known competing financial interests or personal
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602 **References**

- 603 Agreste, 2022a. Agreste Agricultural statistical database.
604 Agreste, 2022b. Graph'Agri 2021. Agreste.
605 Agreste, 2021. Bilan d'approvisionnement agroalimentaire 2019-2020 (Chiffres et Données
606 No. 13).
607 Agreste, 2000. Bilan d'approvisionnement agroalimentaire 1993-1998 (Chiffres et Données
608 No. 126).

- Asai, M., Moraine, M., Ryschawy, J., de Wit, J., Hoshide, A.K., Martin, G., 2018. Critical factors for crop-livestock integration beyond the farm level: A cross-analysis of worldwide case studies. *Land Use Policy* 73, 184–194. <https://doi.org/10.1016/j.landusepol.2017.12.010>
- Atinkut, H.B., Yan, T., Zhang, F., Qin, S., Gai, H., Liu, Q., 2020. Cognition of agriculture waste and payments for a circular agriculture model in Central China. *Sci. Rep.* 10, 10826. <https://doi.org/10.1038/s41598-020-67358-y>
- Bai, Z., Fan, X., Jin, X., Zhao, Z., Wu, Y., Oenema, O., Velthof, G., Hu, C., Ma, L., 2022. Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. *Nat. Food* 3, 152–160. <https://doi.org/10.1038/s43016-021-00453-z>
- Bai, Z., Ma, L., Jin, S., Ma, W., Velthof, G.L., Oenema, O., Liu, L., Chadwick, D., Zhang, F., 2016. Nitrogen, Phosphorus, and Potassium Flows through the Manure Management Chain in China. *Environ. Sci. Technol.* 50, 13409–13418. <https://doi.org/10.1021/acs.est.6b03348>
- Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., Tichit, M., 2014. Agroecological principles for the redesign of integrated crop–livestock systems. *Eur. J. Agron.* 57, 43–51. <https://doi.org/10.1016/j.eja.2013.09.010>
- Bux, C., Amicarelli, V., 2022. Separate collection and bio-waste valorization in the Italian poultry sector by material flow analysis. *J. Mater. Cycles Waste Manag.* 24, 811–823. <https://doi.org/10.1007/s10163-022-01366-0>
- Cameira, M.R., Rolim, J., Valente, F., Faro, A., Dragosits, U., Cordovil, C.M. d. S., 2019. Spatial distribution and uncertainties of nitrogen budgets for agriculture in the Tagus river basin in Portugal – Implications for effectiveness of mitigation measures. *Land Use Policy* 84, 278–293. <https://doi.org/10.1016/j.landusepol.2019.02.028>
- Cappelaere, L., Le Cour Grandmaison, J., Martin, N., Lambert, W., 2021. Amino Acid Supplementation to Reduce Environmental Impacts of Broiler and Pig Production: A Review. *Front. Vet. Sci.* 8, 689259. <https://doi.org/10.3389/fvets.2021.689259>
- Chan, I., Franks, B., Hayek, M.N., 2022. The ‘sustainability gap’ of US broiler chicken production: trade-offs between welfare, land use and consumption. *R. Soc. Open Sci.* 9, 210478. <https://doi.org/10.1098/rsos.210478>
- Chatzimpiros, P., Barles, S., 2013. Nitrogen food-print: N use related to meat and dairy consumption in France. *Biogeosciences* 10, 471–481. <https://doi.org/10.5194/bg-10-471-2013>
- Čičková, H., Newton, G.L., Lacy, R.C., Kozánek, M., 2015. The use of fly larvae for organic waste treatment. *Waste Manag.* 35, 68–80. <https://doi.org/10.1016/j.wasman.2014.09.026>
- CITEPA, 2022. Rapport National d’Inventaire pour la France au titre de la Convention cadre des Nations Unies sur les Changements Climatiques et du Protocole de Kyoto. CITEPA, Paris.
- CITEPA, 2020a. Floréal Inventory Report. CITEPA.
- CITEPA, 2020b. Floréal Inventory Report database 1990-2018 [WWW Document]. URL https://www.citepa.org/wp-content/uploads/BDD_FLOREAL_1990_2018.xlsx
- Cordell, D., White, S., 2014. Life’s Bottleneck: Sustaining the World’s Phosphorus for a Food Secure Future. *Annu. Rev. Environ. Resour.* 39, 161–188. <https://doi.org/10.1146/annurev-environ-010213-113300>
- De Boer, I.J.M., Van Der Togt, P.L., Grossman, M., Kwakkel, R.P., 2000. Nutrient flows for poultry production in The Netherlands. *Poult. Sci.* 79, 172–179. <https://doi.org/10.1093/ps/79.2.172>

- Diry, J.-P., 1985. L'industrialisation de l'élevage en France: économie et géographie des
filières avicoles et porcines. Ophrys, Marseille.
- Dourmad, J.-Y., Guilbaud, T., Tichit [†], M., Bonaudo, T., 2019. Les productions animales
dans la bioéconomie. INRA Prod. Anim. 205–220.
<https://doi.org/10.20870/productions-animales.2019.32.2.2485>
- Dourmad, J.Y., Méda, B., 2021. 2. Towards increased nitrogen efficiency in pig and poultry
production. Anim. - Sci. Proc. 12, 247–249.
<https://doi.org/10.1016/j.anscip.2022.01.003>
- Du, Z., Liu, Y., Ding, J., Zou, G., Hu, Z., Zhang, R., 2022. Evaluation of the local decoupling
of livestock and cropland in the Huang-Huai-Hai region. Environ. Sci. Pollut. Res.
<https://doi.org/10.1007/s11356-022-21993-2>
- Einarsson, R., Sanz-Cobena, A., Aguilera, E., Billen, G., Garnier, J., van Grinsven, H.J.M.,
Lassaletta, L., 2021. Crop production and nitrogen use in European cropland and
grassland 1961–2019. Sci. Data 8, 288. <https://doi.org/10.1038/s41597-021-01061-z>
- Eurostat, 2022. Farm structure survey.
- FAOSTAT, 2022. FAO statistical database. The Food and Agriculture Organization of the
United Nations., Rome.
- FranceAgriMer, 2021. Compétitivité de la filière française volaille.
- Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B.,
Cosby, B.J., 2003. The Nitrogen Cascade. BioScience 53, 341–356.
[https://doi.org/10.1641/0006-3568\(2003\)053\[0341:TNC\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2)
- Garcia-Launay, F., Dusart, L., Espagnol, S., Laisse-Redoux, S., Gaudré, D., Méda, B.,
Wilfart, A., 2018. Multiobjective formulation is an effective method to reduce
environmental impacts of livestock feeds. Br. J. Nutr. 120, 1298–1309.
<https://doi.org/10.1017/S0007114518002672>
- Garrett, R.D., Niles, M.T., Gil, J.D.B., Gaudin, A., Chaplin-Kramer, R., Assmann, A.,
Assmann, T.S., Brewer, K., de Faccio Carvalho, P.C., Cortner, O., Dynes, R.,
Garbach, K., Kebreab, E., Mueller, N., Peterson, C., Reis, J.C., Snow, V., Valentim, J.,
2017. Social and ecological analysis of commercial integrated crop livestock systems:
Current knowledge and remaining uncertainty. Agric. Syst. 155, 136–146.
<https://doi.org/10.1016/j.agsy.2017.05.003>
- Garrett, R.D., Ryschawy, J., Bell, L.W., Cortner, O., Ferreira, J., Garik, A.V.N., Gil, J.D.B.,
Klerkx, L., Moraine, M., Peterson, C.A., dos Reis, J.C., Valentim, J.F., 2020. Drivers
of decoupling and recoupling of crop and livestock systems at farm and territorial
scales. Ecol. Soc. 25, art24. <https://doi.org/10.5751/ES-11412-250124>
- Groenestein, C.M., Hutchings, N.J., Haenel, H.D., Amon, B., Menzi, H., Mikkelsen, M.H.,
Misselbrook, T.H., van Bruggen, C., Kupper, T., Webb, J., 2019. Comparison of
ammonia emissions related to nitrogen use efficiency of livestock production in
Europe. J. Clean. Prod. 211, 1162–1170. <https://doi.org/10.1016/j.jclepro.2018.11.143>
- Harchaoui, S., Chatzimpiros, P., 2018. Energy, Nitrogen, and Farm Surplus Transitions in
Agriculture from Historical Data Modeling. France, 1882-2013.: Energy, Nitrogen,
and Farm Surplus Transitions. J. Ind. Ecol. <https://doi.org/10.1111/jiec.12760>
- Harchaoui, S., Chatzimpiros, P., 2017. Reconstructing production efficiency, land use and
trade for livestock systems in historical perspective. The case of France, 1961–2010.
Land Use Policy 67, 378–386. <https://doi.org/10.1016/j.landusepol.2017.05.028>
- Heinke, J., Lannerstad, M., Gerten, D., Havlík, P., Herrero, M., Notenbaert, A.M.O., Hoff, H.,
Müller, C., 2020. Water Use in Global Livestock Production—Opportunities and
Constraints for Increasing Water Productivity. Water Resour. Res. 56.
<https://doi.org/10.1029/2019WR026995>

- Huis, A., 2022. Edible insects: Challenges and prospects. *Entomol. Res.* 52, 161–177. <https://doi.org/10.1111/1748-5967.12582>
- Hutchings, N.J., Sørensen, P., Cordovil, C.M. d. S., Leip, A., Amon, B., 2020. Measures to increase the nitrogen use efficiency of European agricultural production. *Glob. Food Secur.* 26, 100381. <https://doi.org/10.1016/j.gfs.2020.100381>
- ITAVI, 2020. Performances techniques et coûts de production en volailles de chair: résultats 2019.
- ITAVI, 2013. Estimation des rejets d'azote – phosphore - potassium calcium - cuivre – et zinc par les élevages avicoles. France.
- Karlsson, J.O., Parodi, A., van Zanten, H.H.E., Hansson, P.-A., Röö, E., 2021. Halting European Union soybean feed imports favours ruminants over pigs and poultry. *Nat. Food* 2, 38–46. <https://doi.org/10.1038/s43016-020-00203-7>
- Kleinpeter, V., Alvanitakis, M., Vigne, M., Wassenaar, T., Lo Seen, D., Vayssières, J., 2023. Assessing the roles of crops and livestock in nutrient circularity and use efficiency in the agri-food-waste system: A set of indicators applied to an isolated tropical island. *Resour. Conserv. Recycl.* 188, 106663. <https://doi.org/10.1016/j.resconrec.2022.106663>
- Laisse, S., Baumont, R., Dusart, L., Gaudré, D., Rouillé, B., Benoit, M., Veyssset, P., Rémond, D., Peyraud, J.-L., 2019. L'efficacité nette de conversion des aliments par les animaux d'élevage: une nouvelle approche pour évaluer la contribution de l'élevage à l'alimentation humaine. *INRA Prod. Anim.* 31, 269–288. <https://doi.org/10.20870/productions-animales.2018.31.3.2355>
- Lasekan, A., Abu Bakar, F., Hashim, D., 2013. Potential of chicken by-products as sources of useful biological resources. *Waste Manag.* 33, 552–565. <https://doi.org/10.1016/j.wasman.2012.08.001>
- Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* 9, 105011. <https://doi.org/10.1088/1748-9326/9/10/105011>
- Le Noë, J., Billen, G., Garnier, J., 2017. How the structure of agro-food systems shapes nitrogen, phosphorus, and carbon fluxes: The generalized representation of agro-food system applied at the regional scale in France. *Sci. Total Environ.* 586, 42–55. <https://doi.org/10.1016/j.scitotenv.2017.02.040>
- Lemaire, G., Franzluebbers, A., Carvalho, P.C. de F., Dedieu, B., 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agric. Ecosyst. Environ.* 190, 4–8. <https://doi.org/10.1016/j.agee.2013.08.009>
- Liu, Q., Wang, J., Bai, Z., Ma, L., Oenema, O., 2017. Global animal production and nitrogen and phosphorus flows. *Soil Res.* 55, 451. <https://doi.org/10.1071/SR17031>
- Loyon, L., 2018. Overview of Animal Manure Management for Beef, Pig, and Poultry Farms in France. *Front. Sustain. Food Syst.* 2, 36. <https://doi.org/10.3389/fsufs.2018.00036>
- Magdelaine, P., Coutelet, G., Duvaléix-Treguer, S., 2015. La contractualisation dans le secteur aviculture chair. *Économie Rurale* 73–86. <https://doi.org/10.4000/economierurale.4573>
- Martel, 2017. Mieux coupler cultures et élevage dans les exploitations d'herbivores conventionnelles et biologiques: une voie d'amélioration de leur durabilité? *Fourrages*, 231, 235–245.
- Martin, G., Moraine, M., Ryschawy, J., Magne, M.-A., Asai, M., Sarthou, J.-P., Duru, M., Therond, O., 2016. Crop–livestock integration beyond the farm level: a review. *Agron. Sustain. Dev.* 36, 53. <https://doi.org/10.1007/s13593-016-0390-x>

- Moraine, M., Duru, M., Nicholas, P., Leterme, P., Therond, O., 2014. Farming system design for innovative crop-livestock integration in Europe. *Animal* 8, 1204–1217. <https://doi.org/10.1017/S1751731114001189>
- Moraine, M., Ramonteu, S., Magrini, M.-B., Choisis, J.-P., 2019. Typologie de projets de complémentarité culture – élevage à l'échelle du territoire en France : de l'innovation technique à l'innovation territoriale. *Innovations Agronomiques* 72, 45-59. <https://doi.org/10.15454/MYICHB>
- Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Glob. Food Secur.* 14, 1–8. <https://doi.org/10.1016/j.gfs.2017.01.001>
- Mozhiarasi, V., Natarajan, T.S., 2022. Slaughterhouse and poultry wastes: management practices, feedstocks for renewable energy production, and recovery of value added products. *Biomass Convers. Biorefinery*. <https://doi.org/10.1007/s13399-022-02352-0>
- Muscat, A., de Olde, E.M., Ripoll-Bosch, R., Van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M., van Ittersum, M.K., de Boer, I.J.M., 2021. Principles, drivers and opportunities of a circular bioeconomy. *Nat. Food* 2, 561–566. <https://doi.org/10.1038/s43016-021-00340-7>
- Nesme, T., Senthilkumar, K., Mollier, A., Pellerin, S., 2015. Effects of crop and livestock segregation on phosphorus resource use: A systematic, regional analysis. *Eur. J. Agron.* 71, 88–95. <https://doi.org/10.1016/j.eja.2015.08.001>
- Odum, E.P., 1989. *Ecology and our endangered life-support systems*. Sinauer Associates, Sunderland, Mass.
- OECD, 2021. *OECD-FAO Agricultural Outlook. 2021-2030*.
- OECD-FAO, 2022. *OECD-FAO Agricultural Outlook 2022-2031*, OECD-FAO Agricultural Outlook. OECD. <https://doi.org/10.1787/f1b0b29c-en>
- Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. *Livest. Sci.* 112, 261–272. <https://doi.org/10.1016/j.livsci.2007.09.007>
- Pampouille, E., Dusart, L., Bonnouvrier, A., Danel, J., Dauguet, S., Désolé, M., Heuzé, V., Lambert, W., Le Bourhis, C., Le Cadre, P., Martin, N., Méda, B., Bouvarel, I., 2021. VOCALIM - Mieux valoriser des matières premières métropolitaines dans l'alimentation des poulets de chair pour améliorer l'autonomie protéique française *Innovations Agronomiques* 82, 425-440. <https://doi.org/10.15454/GYBR-S265>
- Peron, L., 2019. *Parcours à haute valeur protéique; Synthèse des essais conduits sur volailles de chair à l'INRA du Magneraud et au Lycée des Sicaudières. SECALIBIO: Sécuriser les systèmes alimentaires en production de monogastriques biologiques*.
- Réséda, 2017. *Enquête 2017: Gisements et valorisations des coproduits des industries agroalimentaires. Réseau pour la sécurité et la qualité des denrées alimentaires*.
- Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering Integrated Crop-Livestock Systems in North America. *Agron. J.* 99, 325–334. <https://doi.org/10.2134/agronj2006.0139>
- Ryschawy, J., Benoit, M., Hostiou, N., Delfosse, C., 2018. Quelles concurrences et synergies entre cultures et élevage dans les territoires de polyculture-élevage? *INRA Prod. Anim.* 30, 363–380. <https://doi.org/10.20870/productions-animales.2017.30.4.2266>
- Ryschawy, J., Joannon, A., Gibon, A., 2014. Mixed crop-livestock farm: definitions and research issues. A review. *Cah. Agric.* 23, 346–356. <https://doi.org/10.1684/agr.2014.0727>
- Sailley, M., Cordier, C., Courtonne, J.-Y., Duflot, B., Cadudal, F., Perrot, C., Brion, A., Baumont, R., 2022. Quantifier et segmenter les flux de matières premières utilisées en

- France par l'alimentation animale. *INRAE Prod. Anim.* 34, 273–292.
<https://doi.org/10.20870/productions-animales.2021.34.4.5396>
- Santonja, G.G., Georgitzikis, K., Scalet, B.M., Montobbio, P., Roudier, S., Sancho, L.D., 2017. Best available techniques (BAT) reference document for the intensive rearing of poultry or pigs. *EUR 28674 EN* 11, 898.
- Schut, A.G.T., Cooleedge, E.C., Moraine, M., Van De Ven, G.W.J., Jones, D.L., Chadwick, D.R., 2021. Reintegration of crop-livestock systems in Europe: an overview. *Front. Agric. Sci. Eng.* 8, 111. <https://doi.org/10.15302/J-FASE-2020373>
- Shepon, A., Eshel, G., Noor, E., Milo, R., 2016. Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. *Environ. Res. Lett.* 11, 105002. <https://doi.org/10.1088/1748-9326/11/10/105002>
- Smil, V., 2000. *Feeding the world: a challenge for the twenty-first century*. MIT Press, Cambridge, Mass. London.
- Steinfeld, H., Gerber, P., Wassenaar, T., Castel, Rosales, M., de Haan, C., 2006. *Livestock's long shadow: environmental issues and options*. Food and Agriculture Organization of the United Nations, Rome.
- Steinfeld, H., Wassenaar, T., 2007. The Role of Livestock Production in Carbon and Nitrogen Cycles. *Annu. Rev. Environ. Resour.* 32, 271–294.
<https://doi.org/10.1146/annurev.energy.32.041806.143508>
- Sutton, M.A., Bleeker, A., Howard, C., Bekunda, M., Grizzetti, B., De Vries, W., van Grinsven, Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., 2013. Our nutrient world: the challenge to produce more food and energy with less pollution ; [global overview on nutrient management]. Centre for Ecology & Hydrology, Edinburgh.
- USDA, 1992. *Weights, Measures, and Conversion Factors for Agricultural Commodities and Their Products*, Economic Research Service in cooperation with the Agricultural Marketing Service, the Agricultural Research Service, and the National Agricultural Statistics Service, U.S. Department of Agriculture. *Agricultural Handbook No. 697*.
- Uwizeye, A., de Boer, I.J.M., Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J.N., Leip, A., Erisman, J.W., Robinson, T.P., Steinfeld, H., Gerber, P.J., 2020. Nitrogen emissions along global livestock supply chains. *Nat. Food* 1, 437–446. <https://doi.org/10.1038/s43016-020-0113-y>
- Uwizeye, A., Gerber, P.J., Schulte, R.P.O., de Boer, I.J.M., 2016. A comprehensive framework to assess the sustainability of nutrient use in global livestock supply chains. *J. Clean. Prod.* 129, 647–658. <https://doi.org/10.1016/j.jclepro.2016.03.108>
- Vaarst, M., Roderick, S., Lund, V., Lockeretz, W., 2004. *Animal health and welfare in organic agriculture*. CABI Pub, Wallingford, Oxon, UK ; Cambridge, MA, USA.
- van Selm, B., Frehner, A., de Boer, I.J.M., van Hal, O., Hijbeek, R., van Ittersum, M.K., Talsma, E.F., Lesschen, J.P., Hendriks, C.M.J., Herrero, M., van Zanten, H.H.E., 2022. Circularity in animal production requires a change in the EAT-Lancet diet in Europe. *Nat. Food* 3, 66–73. <https://doi.org/10.1038/s43016-021-00425-3>
- Van Zanten, H.H.E., Van Ittersum, M.K., De Boer, I.J.M., 2019. The role of farm animals in a circular food system. *Glob. Food Secur.* 21, 18–22.
<https://doi.org/10.1016/j.gfs.2019.06.003>
- Velasco-Muñoz, J.F., Mendoza, J.M.F., Aznar-Sánchez, J.A., Gallego-Schmid, A., 2021. Circular economy implementation in the agricultural sector: Definition, strategies and indicators. *Resour. Conserv. Recycl.* 170, 105618.
<https://doi.org/10.1016/j.resconrec.2021.105618>
- Wang, Y., Yuan, Z., Tang, Y., 2021. Enhancing food security and environmental sustainability: A critical review of food loss and waste management. *Resour. Environ. Sustain.* 4, 100023. <https://doi.org/10.1016/j.resenv.2021.100023>

- Wilfart, A., Espagnol, S., Dauguet, S., Tailleur, A., Gac, A., Garcia-Launay, F., 2016. ECOALIM: A dataset of environmental impacts of feed ingredients used in French animal production. *PloS One* 11.
- Wilfart, A., Gac, A., Salaün, Y., Aubin, J., Espagnol, S., 2021. Allocation in the LCA of meat products: is agreement possible? *Clean. Environ. Syst.* 2, 100028. <https://doi.org/10.1016/j.cesys.2021.100028>
- Wilkins, R.J., 2008. Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 517–525. <https://doi.org/10.1098/rstb.2007.2167>
- Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F.N., Smith, P., Campbell, N., Jain, A.K., 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nat. Food* 2, 724–732. <https://doi.org/10.1038/s43016-021-00358-x>
- Zhang, J., Zhang, Jia, Li, J., Tomerlin, J.K., Xiao, X., ur REHMAN, K., Cai, M., Zheng, L., Yu, Z., 2021. Black soldier fly: A new vista for livestock and poultry manure management. *J. Integr. Agric.* 20, 1167–1179. [https://doi.org/10.1016/S2095-3119\(20\)63423-2](https://doi.org/10.1016/S2095-3119(20)63423-2)
- Zhang, X., Zou, T., Lassaletta, L., Mueller, N.D., Tubiello, F.N., Lisk, M.D., Lu, C., Conant, R.T., Dorich, C.D., Gerber, J., Tian, H., Bruulsema, T., Maaz, T.M., Nishina, K., Boudirsky, B.L., Popp, A., Bouwman, L., Beusen, A., Chang, J., Havlík, P., Leclère, D., Canadell, J.G., Jackson, R.B., Heffer, P., Wanner, N., Zhang, W., Davidson, E.A., 2021. Quantification of global and national nitrogen budgets for crop production. *Nat. Food* 2, 529–540. <https://doi.org/10.1038/s43016-021-00318-5>