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

3

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17 **Abstract**

18 Poultry is the fastest growing livestock sector worldwide, but it remains underrepresented in
19 studies of crop-livestock integration and circular agricultural systems. This study examined
20 the concept of circularity applied to the poultry supply chain by analyzing nitrogen (N) flows
21 at the national scale for France. Our results show that N-use efficiency of the poultry sector
22 increased from 39% in 1990 to 44% in 2020. In contrast, N self-sufficiency barely changed at
23 10%, and imports of poultry products increased sixfold. Of the total annual input of 376 kt N,
24 20% becomes food, 24% is recycled, and 56% is lost to the environment. We explore two
25 pathways to increase circularity: (i) increasing N-use efficiency at each step of the supply
26 chain as well as the percentage of manure N transferred to crop production and by-products
27 used from slaughterhouse and processing industries and (ii) changing feed rations by using
28 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

53 (N) emissions, contributing ca. one-third of global anthropogenic emissions (Uwizeye et al.,
54 2020). The geographic decoupling of livestock and crop systems, associated with
55 specialization of agricultural systems, is currently the main driver behind changes in the
56 biogeochemical cycles of N (Galloway et al., 2003; Sutton et al., 2013), phosphorus (Cordell
57 and White, 2014; Nesme et al., 2015), and carbon (Steinfeld and Wassenaar, 2007). Globally,
58 the consumption of animal protein has more than quadrupled from 1961 to the present
59 (FAOSTAT, 2022) and is expected to increase by 14% by 2030 (OECD, 2021). The challenge
60 in future decades is to meet this increasing demand for animal-based foods while also
61 reducing environmental impacts of livestock production.

62 Integrated crop-livestock systems (ICLS) provide sustainable strategy for livestock production
63 that can meet these environmental challenges (Ryschawy et al., 2014; Schut et al., 2021).
64 ICLS combines crop and livestock production on the same farm or group of farms to improve
65 soil fertility and nutrient cycling by promoting synergies and complementarities between crop
66 and livestock systems. Several studies explored the driving forces for and barriers to
67 implementing ICLS at the farm scale (Bonaudo et al., 2014; Martel, 2017; Moraine et al.,
68 2014) and, more recently, at the territorial scale (Asai et al., 2018; Garrett et al., 2020;
69 Moraine et al., 2019). These studies identified environmental (Lemaire et al., 2014; Martin et
70 al., 2016; Ryschawy et al., 2018) and economic advantages (Russelle et al., 2007; Wilkins,
71 2008) of ICLS over specialized systems. Similarly, a wider concept of a circular economy has
72 been developed to address sustainability issues in agri-food systems by focusing on
73 biophysical flows (Muscat et al., 2021) to reconnect crop and livestock production as well as
74 other components of these systems, such as food and feed processing and waste management
75 (Wang et al., 2021). Within this framework, livestock can recycle by-products and biomass
76 into food and manure and then restore its critical role in closing biogeochemical flows (van
77 Selm et al., 2022; Van Zanten et al., 2019).

78 However, among livestock species, ICLS and circular agriculture of monogastric species,
79 especially poultry, have been studied much less than those of ruminants (Garrett et al., 2017)
80 (see mini-review in Supplementary Information, Fig. S1). This is paradoxical from an
81 historical perspective, since in preindustrial agriculture, monogastric species served mainly as
82 recyclers or scavengers of low-quality feed, such as agricultural waste, leftovers, and forage
83 (Vaarst et al., 2004) on the farm and contributed little to the total amount of animal protein
84 produced. For instance, production data for poultry were not reported in agricultural statistics
85 in France until the late 1960s (Diry, 1985). In contrast, the modern poultry sector is
86 specialized and supported by high-quality nutrient feed. Poultry is a highly efficient protein
87 producer within the livestock sector (Dourmad and Méda, 2021; Smil, 2000) and provides
88 26% of all animal products worldwide. Globally, the amount of protein in poultry meat and
89 eggs has increased ninefold from 1961 to the present, and in the next decade, poultry
90 consumption will comprise more than half of the world's growth in meat consumption
91 (OECD-FAO, 2022). Recent studies at the national scale (Bai et al., 2016) and global scale
92 (Liu et al., 2017; Uwizeye et al., 2020) have developed models to assess nutrient flows along
93 the entire chain of livestock production systems. However, there is no integrated framework
94 that quantifies all nutrient flows at each step of the supply chain and defines circularity for a
95 specific livestock category such as poultry. To date, only De Boer *et al.* (2000) have
96 examined N flows of the poultry sector at the national scale, for the Netherlands. In addition,
97 few studies have considered nutrient flows associated with the international trade of feed and
98 livestock products (Chatzimpiros and Barles, 2013), but doing so is critical in order to
99 examine the potential to mitigate nutrient losses. Addressing this gap is crucial to provide
100 pathways to sustainable agricultural systems and to understand how poultry convert feed into
101 meat or eggs and play a role in the circularity of nutrients by returning feed and manure back
102 to the soil.

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

108

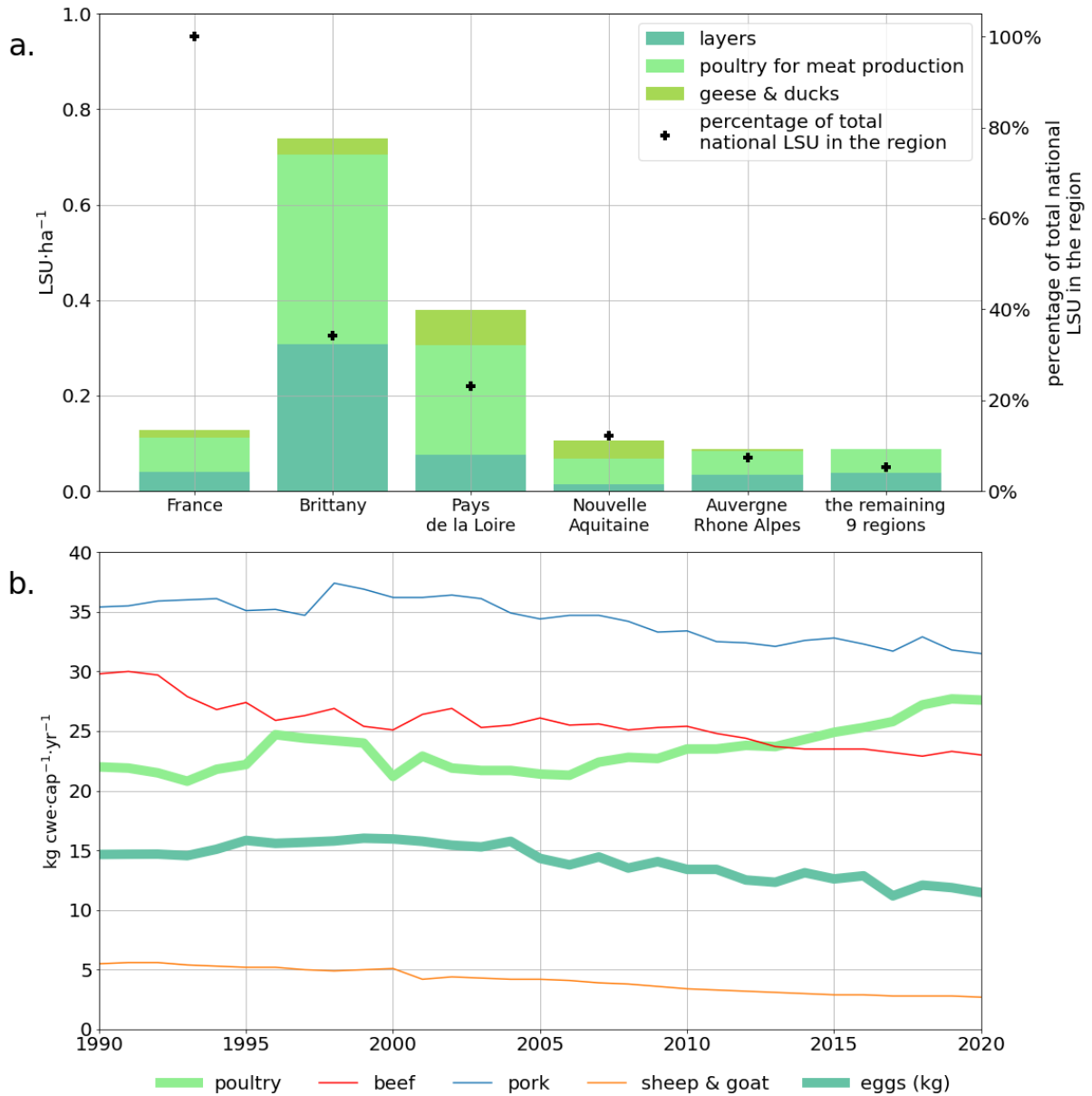
109 **2. Materials and methods**

110

111 *2.1. Overview of the poultry supply sector in France*

112 The French poultry sector produces 1.81 Mt carcass-weight equivalent (cwe) of poultry and
113 0.84 Mt of eggs annually for domestic consumption and exports (Agreste, 2022a). France
114 currently has ca. 297 million head of poultry, which represent 18% of all livestock head in
115 France. The layer sector represents 46 million laying hens that produce eggs for consumption
116 and 36 million hatching hens and pullets. Broiler production is the largest subsector of the
117 poultry meat supply chain (63%, with 1.1 Mt cwe), followed by turkey (20%) and duck (7%)
118 (Supplementary Fig. S2). The remaining production includes spent laying hens, guinea fowl,
119 and geese (Agreste, 2022a). A total of 52% of French broiler farms are specialized. Poultry
120 meat and eggs are produced mainly in western France, with 60% of the national poultry
121 population in Brittany and Pays de la Loire (Fig. 1a). This sector is supported by an increase
122 in national demand, with poultry meat representing 31% of total per capita meat consumption
123 in 2020 (Agreste, 2022b). Unlike other meat consumption, French per capita consumption of
124 all poultry meat increased by 25% over the past 30 years (Fig. 1b), reaching 29 kg cwe per
125 capita per year and replacing beef and pork (Agreste, 2022b). In contrast, national per capita
126 egg consumption decreased by 21% over the same period. Poultry production in France is

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



131
 132 **Fig. 1. Overview of the French poultry sector.** a. Livestock unit (LSU) density per ha of
 133 agricultural land for France and the main administrative regions (left axis) and their respective
 134 percentages of total national LSU (right axis) in 2020. b. National per capita meat and egg
 135 consumption in kg carcass-weight equivalent (cwe) per year from 1990 to 2020.

136

137 *2.2.System boundaries*

138 The system under study was the poultry supply chain in metropolitan France from 1990 to
139 2020. In this study, poultry included three categories: layers, poultry for meat production
140 (including broilers, turkeys and guinea fowls), and geese and ducks (Supplementary Table
141 S1). The system boundaries included four stages of the supply chain: feed production
142 (domestic and foreign), livestock production, manure management, and animal slaughtering
143 and processing. Retail and distribution were not included. The analysis was based on data
144 from French annual agricultural statistics (Agreste, 2022a), national inventory emission data
145 (CITEPA, 2022, 2020a, 2020b), and statistical databases for international trade (Agreste,
146 2022a; FAOSTAT, 2022). All assumptions and data sources are summarized in
147 Supplementary Tables S1-S3.

148

149 *2.3.Nitrogen flows and budget*

150 The methods used to analyze N flows (Fig. 2) in the national poultry supply chain were
151 adapted from the framework developed by Uwizeye *et al.* (2016). We determined an N budget
152 for each stage in the poultry supply chain. National statistics (Agreste, 2022a) provided
153 domestic poultry production data for carcass weight and the number of eggs produced. For
154 each poultry production category, the percentage of carcass weight in animal live weight
155 (LW) (dressing percentage), the N content of domestic live animals and eggs, and the
156 percentage of human-edible protein in LW were compiled from different sources (ITAVI,
157 2013; Laisse *et al.*, 2019; Le Noë *et al.*, 2017; USDA, 1992) (Table 1). These parameters,
158 which we assumed remained constant over the period, allowed us to estimate the distribution
159 between human-edible (meat and offal) and non-human-edible products (bones, skin, head,
160 feet, and other removed parts) after slaughtering and processing (Le Noë *et al.*, 2017).

161 **Table 1. Coefficients used to calculate feed and animal production: the N content in live**
 162 **animals or eggs, percentage of carcass weight in animal live weight (dressing**
 163 **percentage), percentage of human-edible protein in live weight, N excretion factors, and**
 164 **feed ration for each poultry category** (CITEPA, 2020a, 2020b; ITAVI, 2013; Laisse et al.,
 165 2019; Le Noë et al., 2017; USDA, 1992). Except for CITEPA (2020b) assumptions of annual
 166 N excretion factors, all other coefficients were assumed to be constant from 1990 to 2020.
 167 The N excretion factor for layers is the mean N-excretion factor weighted by flock size for
 168 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 (%)				laying hens:		
	2.89	3.58	3.84	2.08	2.88	2.80
				eggs:		
				1.79		
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

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

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

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

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

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

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

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

176

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

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

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

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

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

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

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

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

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

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

187 1):

$$188 \quad N_{manure} = \sum_i Heads_i \times \frac{F_i^{exc}}{1000} \quad (\text{eq. 1})$$

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

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

191

192 The fate of excreted N in buildings, on runs, during storage, and in manure transferred to crop
193 production, as well as N loss, was calculated using a detailed annual N-budget analysis from
194 1990 to 2018 (CITEPA, 2020b) that we supplemented for 2019 and 2020. Manure transferred
195 to crop production was divided between that transferred to produce poultry feed ($N_{poultry}^{manure}$, kt
196 $N \cdot yr^{-1}$ as internal flow) or non-poultry feed ($N_{non-poultry}^{manure}$, kt $N \cdot yr^{-1}$). We assumed that the
197 distribution of manure applied to poultry feed crops (N_{inputs}^{manure} , kt $N \cdot yr^{-1}$) between poultry
198 manure ($N_{poultry}^{manure}$) and manure for other livestock categories (N_{other}^{manure} , kt $N \cdot yr^{-1}$) was identical
199 to the average distribution of manure applied to all crops harvested in France and reported by
200 CITEPA (2020a, 2020b). In the livestock-production stage, N-retention efficiency (%)
201 equaled the N content in live animals and eggs divided by total feed N, times 100. In the
202 manure management stage, the manure N recovery rate (%) equaled the N transferred to
203 cropland after N losses in buildings, storage and spreading (but not N transformation in the
204 soil) divided by the total N excreted in buildings (excluding manure transferred on runs),
205 times 100. After the slaughtering and processing stage, the conversion efficiency of edible-
206 product N (%) was calculated as the product of N-retention efficiency and the percentage of
207 human-edible N in LW.

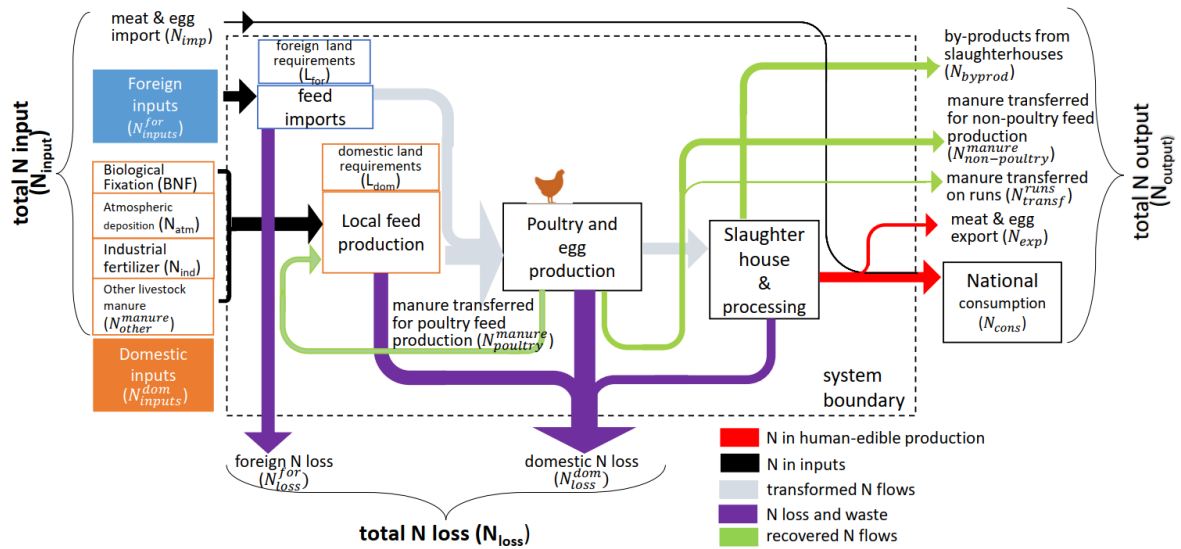
208 Agricultural statistics do not include information on feed per livestock category (Harchaoui
209 and Chatzimpiros, 2017). The composition of feed rations was reconstructed from the recent
210 analysis of Sailley *et al.* (2022), who covered all livestock categories in France for 2015
211 (Table 1).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

217 products due to lack of reported data. We assumed that feed rations remained constant from
 218 1990 to 2020 (Table 1) for each poultry category. The percentages of cereals and oilseed
 219 cakes likely varied, but there were not enough specific data to consider these differences over
 220 time (Supplementary Table S2).

221 The total annual N fertilization inputs required to produce poultry feed in France ($N_{inputs}^{dom,tot}$, kt
 222 $N \cdot yr^{-1}$) were calculated assuming a mean national crop N-use efficiency ($NUE_{crop, \%}$) reported
 223 in a recent study (Einarsson et al., 2021), which we supplemented for 2020 and expressed as
 224 (Eq. 2):

$$225 \quad N_{inputs}^{dom,tot} = BNF + N_{atm} + N_{ind} + N_{inputs}^{manure} \quad (\text{eq. 2})$$

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



241

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

245

246 2.4. Land requirements

247 Land requirements equaled the sum of the agricultural area required to feed poultry
 248 (Harchaoui and Chatzimpiros, 2017). We excluded the land required to feed the animals used
 249 to produce imported meat and egg products. The direct land occupation of livestock buildings,
 250 which is currently ca. 2 490 ha in France (ITAVI, 2013), was considered negligible and thus
 251 excluded. For each year, land requirements were calculated by dividing the quantity of each
 252 feed ingredient by the crop yield required to produce it (FAOSTAT, 2022). For oilseed cakes,
 253 the land requirement for oilseed grain was divided between the co-products (oil and cake) of
 254 grain processing using an economic allocation factor, in accordance with EcoAlim
 255 recommendations (Wilfart et al., 2016). Land requirements were divided between domestic
 256 (L_{dom} , ha) and foreign land (L_{for} , ha) based on the availability of each feed ingredient at the
 257 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):

$$275 \quad N U E_{s e c t o r} (\%) = \frac{N_{o u t p u t}}{N_{i n p u t}} \quad (\text{eq. 3})$$

$$276 \quad R_{l o s s} (\text{kg N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}) = \frac{N_{l o s s}^{d o m}}{L_{d o m}} \quad (\text{eq. 4})$$

$$277 \quad N_{s e l f-s u f f i c i e n c y} (\%) = \frac{(N_{a t m}+B N F)}{N_{i n p u t}} \quad (\text{eq. 5})$$

$$278 \quad N_{r e c y c l i n g} (\%) = \frac{(N_{b y-p r o d}+N_{n o n-p o u l t r y}^{m a n u r e}+N_{p o u l t r y}^{m a n u r e})}{N_{i n p u t}} \quad (\text{eq. 6})$$

279 where

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

292

293 *2.6.Sensitivity and uncertainty analysis*

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

304 **3. Results and discussion**

305 *3.1. Nitrogen flows in the poultry supply chain in France*

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

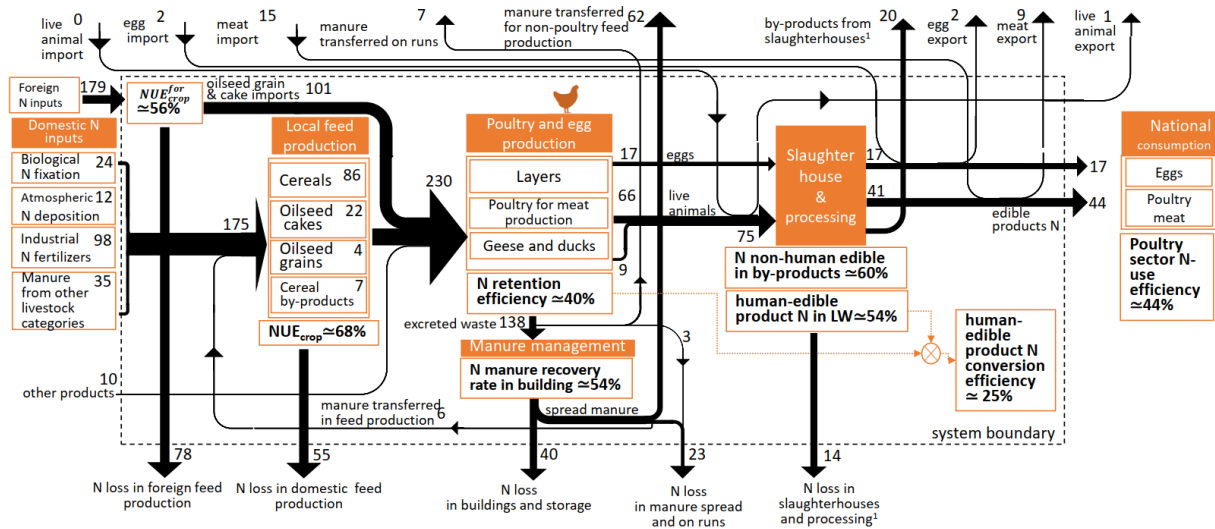
322 Poultry feed comprises 230 kt N per year, mainly concentrates, divided among poultry for
323 meat production (60%), layers (30%), and geese and ducks (10%). This total feed estimate
324 lies at the lower end of the 20% confidence interval of the estimate of Saille *et al.* (2022).
325 Imported oilseed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

329 25% from other European countries, and 15% from other countries (mainly Argentina and
330 marginally India) in that year. Foreign N inputs required for feed imports (179 kt N) are
331 higher than domestic N inputs for local feed (169 kt N) due to the difference in crop N-use
332 efficiency between France ($NUE_{crop} = 68\%$) and foreign exporter countries such as Brazil
333 ($NUE_{crop}^{for} = 55\%$). The poultry sector also depends indirectly on N upstream of feed production
334 in the form of industrial N fertilizers, estimated at 98 kt N, which represents 6% of industrial
335 N fertilizers used nationally in agriculture.

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

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

354 decoupling of nutrient flows between countries. In addition, imports and exports expressed in
355 N conceal the fact that the kinds of products exchanged differ, with cuts of heavy chickens
356 (ca. 2.5 kg LW at slaughter) imported and light chickens (1.4 kg LW at slaughter) exported.
357 N self-sufficiency of poultry sector is estimated at 10% (Table 2) and reflects the high
358 dependence on both industrial N fertilizers and foreign N inputs for feed imports. $N_{\text{self-sufficiency}}$
359 can be compared to the overall N self-sufficiency of agriculture in France, estimated at 19%
360 (Harchaoui and Chatzimpiros, 2018). We estimate that the N recycling rate is nearly 23%.
361 Interestingly, flows of recycled N (88 kt N), split between 23% in by-products from
362 slaughterhouses and 77% in transferred manure, are larger than the final N consumption (61
363 kt N). Overall, our calculations indicate that the poultry supply chain is 44% N efficient (Fig.
364 3) with total annual input of 376 kt N (Fig. 2). Improving efficiency in each step of the chain
365 would decrease N emissions and exposure to risks associated with importing industrial N
366 fertilizer and soybeans, such as supply disruption or price volatility.
367 The sensitivity analysis (Supplementary Table S4) highlights that NUE_{crop} and the manure N
368 recovery rate influenced the four circularity indicators the most. In addition, we estimate that
369 R_{loss} and $N_{\text{recycling}}$ had the highest uncertainty (17-18%) (Table 2, Supplementary Table S6).
370
371



372
 373 **Fig. 3. Simplified diagram of nitrogen (N) flows per year (kt N·yr⁻¹) in the French**
 374 **poultry supply chain in 2020.** N-use efficiency is calculated in each step of the supply chain
 375 for crop N-use efficiency for feed imported from foreign countries (NUE_{crop}^{for}) or produced
 376 domestically (NUE_{crop}), N-retention efficiency, the percentage of N in non-human-edible
 377 products that is recovered in by-products, and percentage of human-edible N in live weight
 378 (LW). The conversion efficiency of edible-product N equals edible-product N divided by feed
 379 N, times 100. N-use efficiency of the poultry sector is estimated across the supply chain
 380 defined by the system boundary. ¹Flows associated with slaughterhouse by-products have
 381 greater uncertainty. Losses during consumption are not included due to lack of data.

382

383 **Table 2. Estimates and uncertainty of circularity indicators of the French poultry sector**
 384 **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

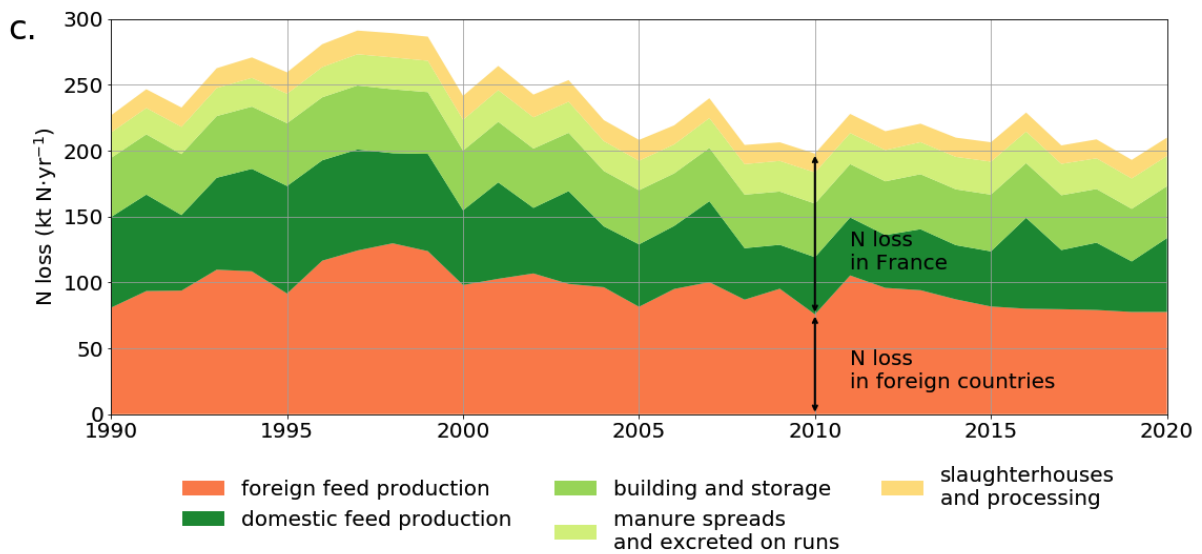
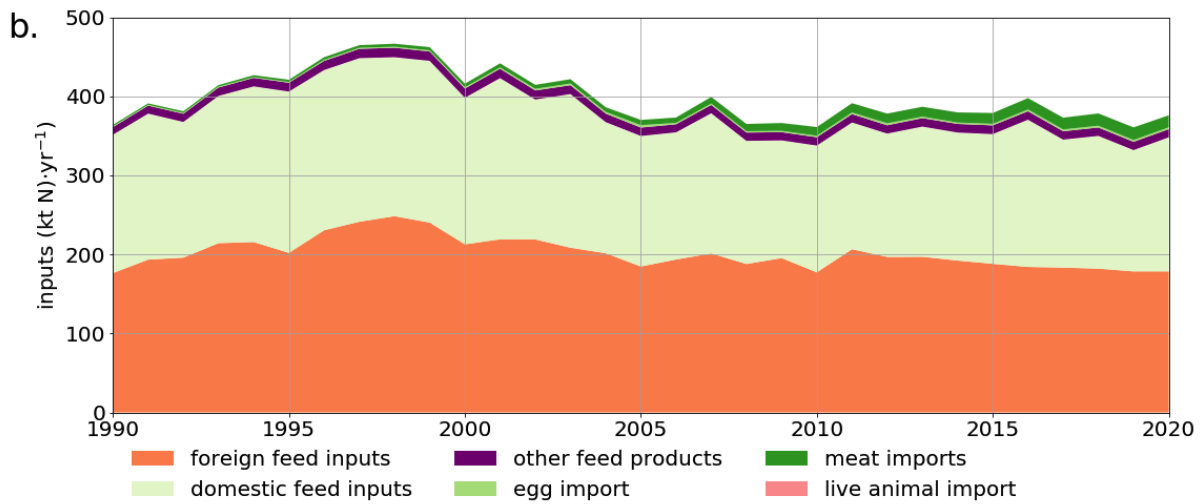
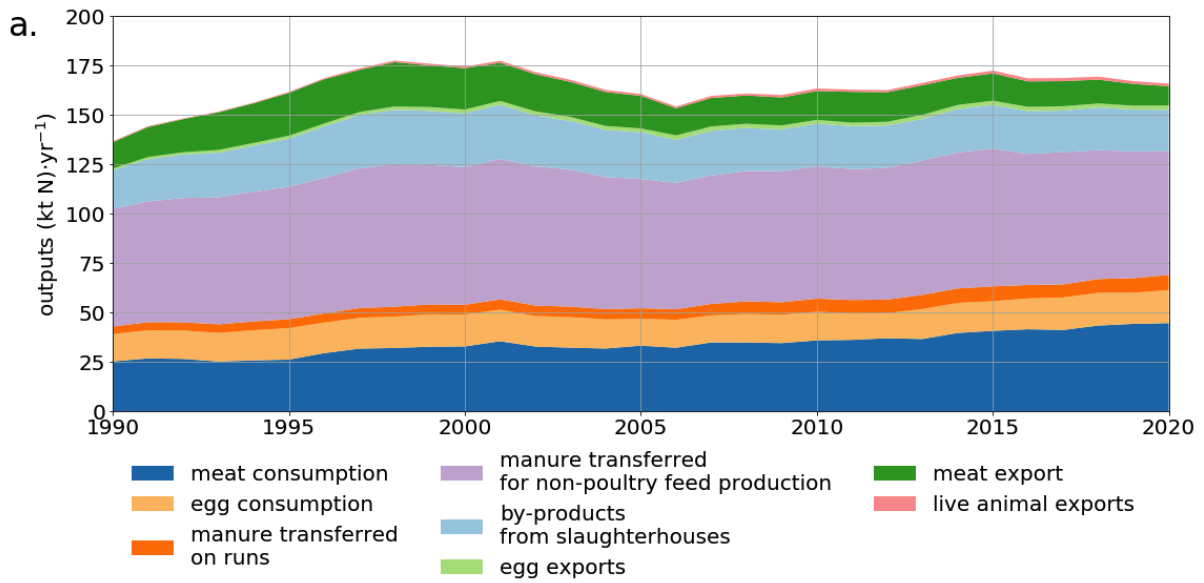
385

386 3.2. Trends in nitrogen flows in poultry supply chain from 1990 to 2020

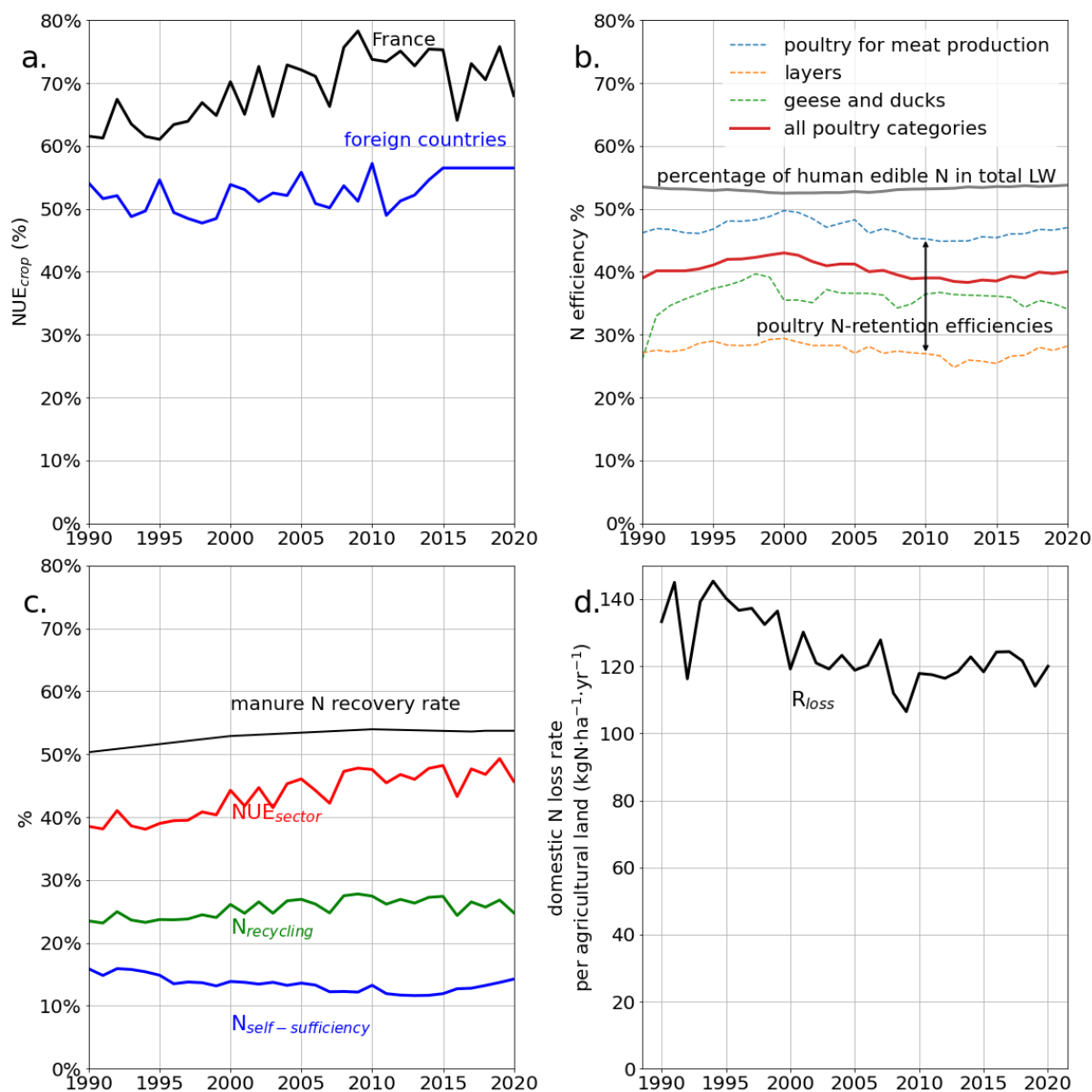
387 From 1990 to 2020, we estimate that N output increased by 20% to 165 kt N per year after
 388 peaking at a 30% increase in 2002 (Fig. 4a). National poultry consumption increased by 27%,
 389 while exports decreased by 25%. Over the same period, total N input increased by only 3%
 390 (Fig. 4b), due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

402 animals and better animal production practices at the farm level. Nevertheless, the N-retention
403 efficiency has plateaued in recent years and may even decrease due to the increased
404 prevalence of production systems that raise intermediate-growth-rate strains. Improved
405 manure management practices increased the manure N recovery rate by 4 percentage points
406 over the period (i.e. from 50% to 54%) (Fig. 5c). Note that manure excreted on runs currently
407 represents 8% of total N excreted, having nearly doubled over the period. This increase
408 coincides with the increased percentage of laying hens with access to a run, from ca. 16% in
409 2000 to 50% in 2020. In addition, N-use efficiency of the entire sector increased by only 4
410 percentage points, and N self-sufficiency remained bound in a narrow range (i.e between 8%
411 and 12%) from 1990 to 2020 (Fig. 5c). The domestic N loss rate decreased by 10% to 125 kg
412 $\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Fig. 5d). In sum, except for increased imports of poultry products, we identified
413 no major changes in circularity for the poultry sector at the national scale from 1990 to 2020
414 according to the four indicators (Fig. 5).

415



418 **Fig. 4. Annual nitrogen (N) budget (kt N·yr⁻¹) of the French poultry supply chain from**
 419 **1990 to 2020. a. Total N output. b. Total N input. c. Total N loss.**



420
 421 **Fig. 5. Crop nitrogen (N)-use efficiency, N-retention efficiency, and N circularity**
 422 **indicators of the French poultry supply chain from 1990 to 2020. a. Crop N-use efficiency**
 423 **in France and foreign countries (Brazil), based on Einarsson *et al.* (2021) and Zhang *et al.***
 424 **(2021), respectively b. N-retention efficiencies for poultry for meat production, layers, and**
 425 **geese and ducks, and percentage of human-edible N in total live weight. The red line is the**
 426 **weighted mean poultry N-retention efficiency for all poultry categories c. Poultry-sector N-**

427 use efficiency (NUE_{sector}), N self-sufficiency ($N_{\text{self-sufficiency}}$), N recycling ($N_{\text{recycling}}$), and
428 manure N recovery rate d . N-loss rate per ha of agricultural area in France used for feed
429 production (R_{loss}). The four circularity indicators are NUE_{sector} , $N_{\text{self-sufficiency}}$, R_{loss} , and
430 $N_{\text{recycling}}$.

431 *3.3.Land requirements*

432 The land required to produce animal feed is another critical indicator of resource use in the
433 poultry sector (Table 3). We estimated it at 1.4 Mha, compared to 12 Mha of total arable land
434 for cereal and oilseed production in France. This is higher than the 1.27 Mha estimated for
435 broiler and laying hen feed in a previous analysis (Dourmad et al., 2019) based on life cycle
436 assessment that included all livestock categories. The differences are most likely due to
437 different assumptions about the feed rations. Of note, our estimated land requirements are one
438 order of magnitude higher than the current land use of specialized poultry farms in France
439 (0.34 Mha; Agreste, 2022a), highlighting the imbalance between high poultry density and
440 available land for feed. These estimates show that 25% of total poultry land requirements lies
441 outside of France (Table 3) and concerns mainly soybean cake imports. Poultry-sector land
442 requirements in foreign countries (0.34) Mha are 79% higher than the total amount of land
443 used for soybeans in France (0.19 Mha) (Agreste, 2022a).

444

445 **Table 3. Feed composition and land requirements for poultry production in France in**
 446 **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

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

450

451 3.4. Circularity management options for the poultry sector

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

457

458 3.4.1. *Business-as-usual pathway*

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

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

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

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

494

495 *3.4.2. Restructuring pathway*

496 In RES, we assume that we can change feed origins in one of two ways. In the first, we
497 relocate 50% of all imported feed production to France. This option requires increasing
498 current domestic land requirements (1.07 Mha) by at least 20% (1.30 Mha), mainly due to
499 25% lower yields of soybeans in France than in Brazil. This estimate is optimistic since it
500 assumes that soybean could be harvested easily in France, even though it has no arable land
501 available. Although the area in France on which soybean is grown has increased by more than
502 70% over the past 30 years, it remains less than 190 000 ha and is used mainly to produce
503 soybeans for human consumption. Any protein crops (e.g. rapeseed, sunflower) or legumes
504 (e.g. lupin) (Pampouille et al., 2021) other than soybeans would likely require even more land
505 due to their lower protein content and yields. This raises questions about the allocation of
506 agricultural land use in France for other livestock categories and competition with production
507 of food for direct human consumption. This result is consistent with a broader analysis of

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

514 The second option is to increase flows of biowaste and by-products from the food industry
515 into feed rations, as encouraged by the EU's "Farm to Fork" strategy. This option was not
516 assessed quantitatively due to a lack of large-scale data. The challenge of this option is to
517 maintain high N-retention efficiency while replacing raw ingredients used in feed with novel
518 protein ingredients that do not compete with human consumption. This requires considering
519 the appropriate ratio of protein to calories in livestock diets. RES requires that feed
520 formulations be guided not only by market prices but by the origin, feed-food competition,
521 and environmental impacts of feed ingredients (Garcia-Launay et al., 2018; Wilfart et al.,
522 2016). Insect-fed poultry production could be a partial solution if the insects are raised on
523 non-human-edible plant residues or organic side streams (Huis, 2022). Free-range
524 management could be oriented towards producing feed (e.g. worms, insects, plants) in
525 outdoor runs. Previous studies on experimental farms have shown that a managed run can
526 provide 10% of DM intake (per day) and improve the feed-conversion ratio by 0.08-0.21
527 depending on the season (Peron, 2019). Another option would be to use manure to produce
528 insects fed to poultry (Čičková et al., 2015; J. Zhang et al., 2021), but it currently has little
529 short-term potential until food industry biowaste and by-product streams are better quantified,
530 and it raises issues about regulation, safety, and animal welfare.

531

532 3.5. Challenges and limits of the framework

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

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

565

566 **4. Conclusion**

567 Our study provides an initial assessment of N flows and circularity in the French poultry
568 sector in an historical perspective. It presents insight into changes in circularity over time
569 using four indicators related to N use efficiency, the N loss rate, N recycling rate and N self-
570 sufficiency. According to our results, more than 56% of total N inputs are currently lost and
571 wasted each year requiring the development of poultry sector-wide strategies to increase
572 circularity and thus reduce losses, especially as the demand for poultry products continue to
573 grow. The sector's low N self-sufficiency, due to its dependence on industrial fertilizers and
574 imported feed, may make it vulnerable to price disruption and supply risks. Two scenarios of
575 possible futures were discussed in this study. Business-as-usual yielded only a small increase
576 in circularity related to technical progress, especially the ability to improve the efficiency with
577 which poultry convert feed into human-edible products, appears to be relatively limited. In
578 comparison, restructuring the sector improved circularity more by increasing manure recovery
579 and recycling of slaughterhouse and processing by-products through the supply chain.
580 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.

590

591 **Declaration of Competing Interest**

592 The authors declare that they have no known competing financial interests or personal
593 relationships that could have appeared to influence the work reported in this paper.

594

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600

601

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