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1 **A review of socio-metabolic research on circularity in agri-food systems and**
2 **pathways to action.**

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23 **Abstract**

24 Circularity in agri-food systems (AFS) has gained popularity as a concept promoted to decrease
25 negative environmental impacts of agriculture and value chains, from the perspective of either
26 nutrient cycling or a circular economy. However, at the global scale, evidence of increased
27 circularity in AFS remains scarce. Research has been critical of the concept of a circular
28 economy, especially socio-metabolic research. Yet, the latter provides a comprehensive
29 framework for analyzing AFS in relation to planetary boundaries through the quantification of
30 material and energy flows. The present review aimed to understand how socio-metabolic
31 research addresses circularity in AFS, renders circularity operational and supports the transition
32 towards strong sustainability. A total of 78 case studies were selected and characterized in terms
33 of their (i) key methodological features, especially whether they addressed circularity as a
34 context, purpose or means, and (ii) their pathways to action through the place of stakeholders
35 and the key drivers of changes related to livestock production. We discuss knowledge gaps for
36 acting on AFS and identify three priorities for transformative socio-metabolic research of AFS:
37 (i) reveal hidden flows, identify system and compartment diversity (ii) assess trade-offs of
38 transitioning to a circular system, including external impacts beyond the territorial scale (iii)
39 strengthen methods for engaging local stakeholders in the design and implementation of the
40 transition.

41 **Keywords:** circularity, social metabolism, material flow analysis, stakeholders, livestock

42 **Acronyms**

43 AFS Agri-food systems

44 CE Circular economy

45 MFA Material flow analysis

46 NUE Nutrient use efficiency

47 SMR Socio-metabolic research

48 SFA Substance flow analysis

49

50 **Introduction**

51 Agri-food systems (AFS) are defined as the chain of activities from agricultural production to
52 consumption, including fertilization, processing, distribution and waste management. They play
53 a critical role in food production and security but face multiple environmental challenges in the
54 preservation of soil, air and water resources (Foley, 2005; Rockström et al., 2009; Tilman et al.,
55 2011; Steffen et al., 2015). Within AFS, livestock systems are under particular scrutiny since
56 they are associated with high greenhouse gas emissions (Herrero et al., 2013; Xu et al., 2021),
57 nitrogen (N) losses (Uwizeye et al., 2020), land footprints for feed (Mottet et al., 2017) and
58 dependence on international trade (e.g., soybeans imported to Europe and China from South
59 America) (Barbieri et al., 2021). The spatial disconnection of crop and livestock production,
60 led by agricultural specialization (Lassaletta et al., 2014) that depends on the use of industrial
61 fertilizers, has also resulted in increased nutrient losses. These environmental pressures are
62 associated in part with the linear design of most AFS, which is depleting natural resources (e.g.
63 energy, water, soil), generating emissions, disrupting climate and biogeochemical cycles as well
64 as generating food waste (Billen et al., 2021; Chrysafi et al., 2022). Circularity in AFS is
65 promoted by institutions throughout the world, in the same way that they have promoted a
66 circular economy (CE) as a pillar of industrial and environmental policies (Kirchherr et al.,
67 2017; Harris et al., 2021). Two aspects of circularity in AFS can be distinguished – CE and
68 nutrient cycling – although the literature rarely does so clearly (Jurgilevich et al., 2016) (Box
69 1). The concept of CE is subject to major criticisms: (i) the physical impossibility of 100%

70 circularity and the incompatibility of circularity with continued growth of material consumption
71 (Grosse, 2010; Giampietro, 2019), (ii) the need to examine and quantify the trade-offs
72 associated with making the economy more circular (Giampietro, 2019) and (iii) social-political
73 implications due to potential conflicts among stakeholders (Bahers et al., 2017; Corvellec et al.,
74 2022). For the authors of these criticisms, CE should be a means to the end of strong
75 sustainability that limits AFS to planetary boundaries, rather than an end in itself (Haas et al.,
76 2020; van Loon et al., 2023). Many of these criticisms come from socio-metabolic research
77 (SMR) (Box 2). For example, Haas et al. (2020) developed four priorities to align CE with those
78 of planetary boundaries: decrease flows (both resource inputs and emission outputs) before
79 increasing circularity rates, decarbonize energy, stabilize material stocks and consider the (un-
80) sustainability of current biomass extraction.

81 Although circularity is a growing focus of agricultural and food policy-makers, current SMR
82 studies of AFS use different methods to qualify and address it. However, there is a lack of
83 homogenization of the drivers of circularity examined in these studies, which are applied in
84 different regions of the world and at different spatial and temporal scales. To address this gap,
85 we performed a systematic review to analyze how SMR examines circularity in AFS and how
86 to render it operational.

87

88 **Box 1. Definition of circularity for agri-food systems**

89 There is no commonly accepted definition of circularity, which is considered in two fields of
90 study:

91 (i) circular economy (CE), which has many definitions (Kirchherr et al., 2017). CE includes
92 mainly the adoption of business models, as well as the development of technologies and systems

93 across supply chains, to increase resource-use efficiency and promote reuse and recycling of
94 materials. Circularity is central to industrial ecology studies (Erkman, 1997) to contrast circular
95 models to current large-scale linear-production models, including agricultural production.
96 Jurgilevich et al. (2016) highlight that implementing CE in agri-food systems (AFS) i) uses
97 practices and technologies that minimize inputs of finite resources, ii) encourages use of
98 renewable resources, iii) decreases loss of natural resources from systems and iv) encourages
99 reusing and recycling unavoidable resource losses in a way that adds the greatest possible value
100 to the AFS. Recently, Muscat et al. (2021) defined five core principles for circular AFS:
101 safeguarding, avoiding, recycling, prioritizing and entropy.

102 (ii) nutrient cycling. According to Boh and Clark (2020), “the central idea is ‘to close the loop’:
103 to reduce consumption, limit waste losses, and increase nutrient recycling at the farm, regional,
104 and national scales”. Circularity approaches go beyond increasing efficiency in nutrient
105 conversion along AFS. Velasco-Muñoz et al. (2021) promote multiscale reuse and recycling of
106 agricultural waste and increasing nutrient flows between animal and crop production. They
107 provide systemic guidelines that combine CE and nutrient cycling to shift agriculture within
108 safe planetary boundaries.

109

110 **Box 2. Socio-metabolic research and agri-food systems**

111 Socio-metabolic research (SMR) focuses on interactions between biophysical and
112 socioeconomic process. It examines the biophysical basis of societies, particularly flows (of
113 materials, substances or energy) within socioeconomic systems and between them and their
114 environment (Haberl et al., 2019). SMR has been applied to agriculture and agri-food systems

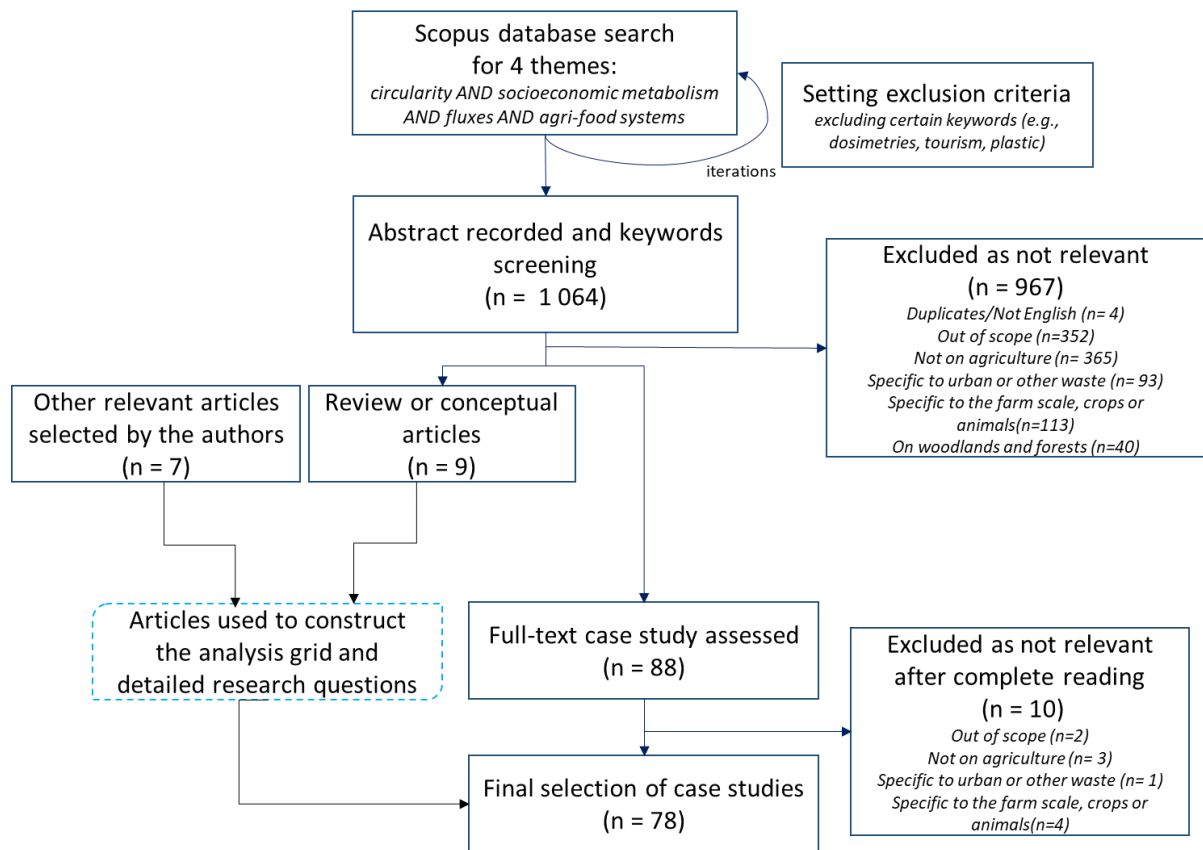
115 (AFS), which lie at the core of societies (LaRota-Aguilera et al., 2022) at multiple temporal and
116 spatial scales (Gabriel et al., 2020).

117 SMR quantitatively analyzes resource use (Fischer-Kowalski and Hüttler, 1998) and
118 environmental footprints (González de Molina et al., 2020) of a system. Unlike traditional
119 economic models or analyses that ignore biophysical constraints of AFS, some authors
120 (Fischer-Kowalski and Haberl, 2007; Erb, 2012) argue that SMR can provide more complete
121 understanding of complex relations within AFS and their relations to their environment.

122

123 **Materials and methods**

124 The literature review followed a two-stage workflow approach inspired by the PRISMA
125 protocol (Moher et al., 2009) (Fig. 1). First, we selected articles using a search query and
126 classified each as a case study, review or conceptual article. Based on the review, as well as
127 conceptual articles that we identified and additional articles that we considered relevant, we
128 then formulated detailed research questions and developed an analysis grid for the selected case
129 studies.



130

131 **Fig 1. Review process used to formulate detailed research questions and identify 78 case**
 132 **studies on how socio-metabolic research examines circularity in agri-food systems**

133

134

135 **Articles selection and classification**

136 The process used to select articles that address circularity and SMR applied to AFS, followed
 137 the following steps (Fig. 1):

138

- The literature review was based on the Scopus® citation database

139

- We constructed the query by combining with the Boolean operator “AND” four search strings in four themes:

140

141

- Circularity: (circular* OR loop OR cycling)

- 142 ○ Socioeconomic metabolism: ("agricultural metabolism" OR "agrarian
143 metabolism" OR "Agrarian Social Metabolism" OR "socioeconomic
144 metabolism" OR "socio-economic metabolism" OR "social-metabolism" OR
145 "MFA" OR "material flow analysis" OR "substance flow
146 analysis" OR "nutrient flow analysis" OR "energy flow analysis" OR "SFA")
- 147 ○ Fluxes: (nutrient OR nitrogen OR phosphorus OR potassium OR
148 material OR energy OR substance)
- 149 ○ AFS: (agro* OR agri* OR food OR livestock)
- 150 • We iterated the query several times and excluded keywords not relevant to the context
151 (see the Supplementary Information Section 1 for the complete search strings and
152 selection process)
- 153 • The search, performed on 15 March 2023 for all articles published before 2023,
154 identified 1064 articles
- 155 • We then selected peer-reviewed and English-language articles based on their title,
156 abstract and keywords . Articles that did not consider AFS, or that focused only on the
157 farm scale, specific types of crops or livestock, urban or food waste, or woodland and
158 forest biomass were excluded (see Table S1 for the full list and exclusion criteria).
- 159 • The articles were classified into three categories: case study, review or conceptual
160 article. After a thorough reading of all articles, 10 additional case studies were omitted
161 using the same exclusion criteria (Fig. 1, Table S1).
- 162 • These steps yielded 78 case studies, 4 reviews and 5 conceptual articles. The reviews
163 and conceptual articles, along with 7 other articles that we selected separately (Table
164 S2), helped us design our two detailed research questions and analysis grid. The present
165 review thus focused on the 78 relevant case studies (Tables S3-S4).
- 166

167 **Formulation of detailed research questions and development of the analysis grid**

168 *Detailed research questions based on previous literature reviews*

169 Previous reviews helped us formulate research questions about the relationships between SMR
170 and circularity. A detailed literature analysis is provided in the Supplementary Information
171 Section 2. Several reviews emphasized practical difficulties in implementing circularity
172 principles, such as socio-technical lock-ins, conflicts over reorganizing material flows (because
173 it creates winners and losers) and concerns about the scale of implementation (Bahers et al.,
174 2017; Corvellec et al., 2022; Marty et al., 2022). We thus focused on relations among SMR,
175 AFS, circularity and action, and more specifically on two components for action: (i)
176 stakeholders (including socioeconomic and political dimensions) and (ii) drivers of changes
177 (i.e. where does one have leverage on the system?). According to Binder (2007), decision-
178 making is driven by personal preferences, social norms and cultural backgrounds, which are
179 difficult to capture in quantitative economic models. In any case, one should question the ability
180 of stakeholders to influence material and nutrient flows (Gabriel et al., 2020). Regarding
181 drivers and mechanisms for changing AFS metabolism and circularity, van der Wiel et al.
182 (2020) reviewed the potential to restore nutrient circularity at the local scale and identified two
183 hotspots: (i) recoupling of crop and livestock production and (ii) recycling of post-consumption
184 food waste. Research on the critical role of livestock in nutrient cycling (de Boer and van
185 Ittersum, 2018; Van Zanten et al., 2019) and in CE (Madelrieux et al., 2023) has also increased
186 greatly in recent years. These studies show the unique ability of livestock production to restore
187 nutrient circularity, from the use of animal feed, and manure to human consumption of animal
188 products.

189 Based on the literature analysis, this review examines how SMR addresses circularity in AFS
190 and pathways to action according to two main research questions:

191 (i) What place do socioeconomic or political dimensions, and stakeholders have in
192 studies that address the circularity of AFS metabolism?

193 (ii) What main drivers related to livestock production have been identified to change
194 AFS metabolism and circularity?

195

196 *Analysis grid*

197 To address these research questions, we built a data-extraction grid that analyzed six features
198 of the 78 case studies: circularity viewpoint, methods, spatial and temporal scales, types of
199 flows, system boundaries and compartments (Table 1). Inspired by the previous work of
200 Scandurra et al. (2023), we defined the circularity viewpoint of the case studies in our review
201 as either a context, a purpose or a means to achieve strong sustainability. Two focuses related
202 to our research questions were also examined: (i) the relation to socioeconomic or political
203 dimensions, and stakeholders (Table 2) and (ii) the main drivers related to livestock production.
204 To identify the latter drivers, we examined the methods of each case study in detail and selected
205 key descriptive variables or input parameters of the livestock supply chain described in the AFS
206 models.

207

208 **Table 1 Key features selected for the review of case studies**

Feature	Criterion	Definition
Circularity viewpoint	Context only	Case studies that mentioned circularity as a context in the introduction, as an indicator in the method (e.g. recycling indicators but no analysis of recycling and a focus of the results on environmental impacts rather than on circularity itself) or as a perspective (e.g. MFA considering recycling issues)
	Purpose	Case studies that identified circularity as an objective of the analysis (i.e. that focused on mechanisms of efficiency and circularity, which are often associated)

	Means	Case studies that examined circularity as a means to decrease environmental impacts (i.e. that consider action mechanisms, including but not limited to circularity and efficiency)
Spatial scale	global, European Union, national, county, city (including metropolitan area)	
Temporal scale	1 year, an average year, decades, centuries, scenario (1 year, but in the future)	
System boundaries and compartments included	production, processing, household consumption, waste management, water management	
Type of flows	Materials	biomass
	Substances	carbon, nitrogen, phosphorus, potassium, magnesium
	Energy	
	Water	
Method	Substance flow analysis (SFA), including spatially explicit SFA	
	Material flow analysis (MFA)	
	Life cycle assessment (LCA), including social LCA	
	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)	
	Participatory approach	
	Energy modeling	

209

210 **Table 2 The roles of stakeholders in the case studies: relation to the socioeconomic or**
211 **political dimension or stakeholders**

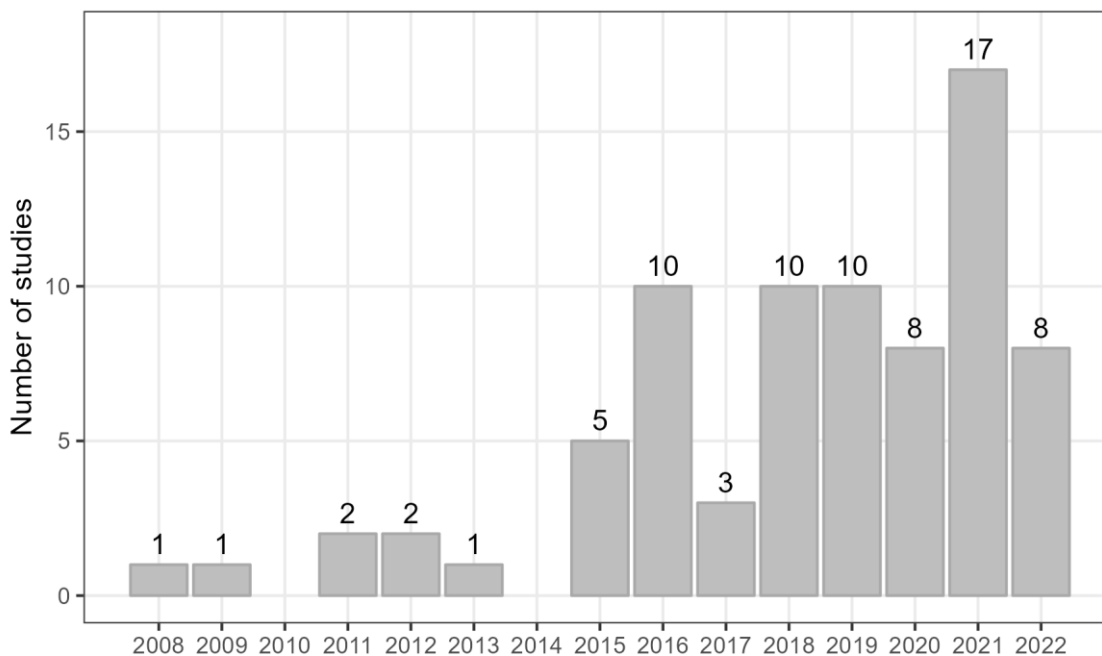
Criterion	Definition
Purpose	The results are discussed, and the idea that they could be used to better guide policy and flow management is stated
Method	Investigation: stakeholders are a source of data and are surveyed (investigation with stakeholders), or political and legislative documents are analyzed (investigation in a political-legislative framework)
	Participatory approach: stakeholders are involved in co-constructing indicators or discussing scenarios
Analysis	The analysis includes relations to socioeconomic variables (e.g. social life cycle assessment)
	Included in modeling: stakeholders are included in agent-based modeling
	Governance of flows: the territorial organization of stakeholders, institutional regulations or place of public action and policies are analyzed
	Assessing stakeholders potential for transformative thinking

212

213 Results

214 Overview of journals

215 The 78 case studies (see Table S4 for the meta-data used) were published in 30 journals (Fig.
216 S1), of which 7 journals represented 61.5% of the total: *Resources, Conservation and Recycling*
217 (13 case studies), *Science of the Total Environment* (10), *Journal of Cleaner Production* (8),
218 *Nutrient Cycling in Agroecosystems* (5), *Agricultural Systems* (4), *Journal of Environmental*
219 *Management* (4) and *Sustainability* (4). Since publication of the first case study in 2008, we
220 observed a threefold increase in the number of studies published per year on circularity in SMR
221 (Fig. 2). The countries studied most were China and European countries (Fig. S2), which can
222 be explained by political incentives in both regions to promote circular AFS and CE strategies
223 (Bleischwitz et al. (2022) for China; Mhatre et al. (2021) for the European Union).



224

225 **Fig 2 Number of case studies reviewed (n=78) published per year**

226 **Features of the case studies**

227 *Circularity viewpoint*

228 *As a context or part of an assessment:* these context-oriented studies assessed the functioning
229 of the flows and compartments of AFS to increase understanding of AFS and compare them
230 temporally and spatially. Circularity was perceived using indicators of recycling (e.g. waste or
231 manure used) but was not the main focus, remaining simply a part of the assessment of AFS
232 metabolism (e.g. Fan et al., 2009). After the assessment, circularity appeared as one of several
233 ways to improve AFS metabolism, which focuses on nutrient sources and sinks to quantify: (i)
234 dependence on imports, (ii) stocks and long-term accumulation of nutrients in AFS
235 compartments, (iii) losses throughout the entire AFS and (iv) nutrient-use efficiencies (NUE).
236 These studies sought to increase understanding of the intensity and dynamics of flows.

237 For studies related to CE, the challenge was to make the invisible visible, as illustrated by the
238 hidden flows and waste of livestock byproducts (e.g. in a beef supply chain (Amicarelli et al.,
239 2021b) or a poultry sector at the national scale (Bux and Amicarelli, 2022)).

240 The studies highlighted several mechanisms for improving AFS metabolism: decreasing
241 absolute flows, in particular to decrease use of non-renewable resources (Gameiro et al., 2019);
242 decreasing production and consumption of products with low conversion efficiency (Adetona
243 and Layzell, 2019); using coproducts (Amicarelli et al., 2021); optimizing land use and using
244 renewable energy (but not necessarily from biomass) (Liu et al., 2017). One study identified a
245 direct stakeholder mechanism: educating consumers about AFS resilience and sustainability
246 (Amicarelli et al., 2021).

247 *As a purpose:* the purpose-oriented studies analyzed circularities in AFS metabolism more
248 deeply and sought to improve the functioning of AFS by improving circularity. They focused
249 on mechanisms of circularity (e.g. decreasing chemical inputs), efficiency (e.g. improving

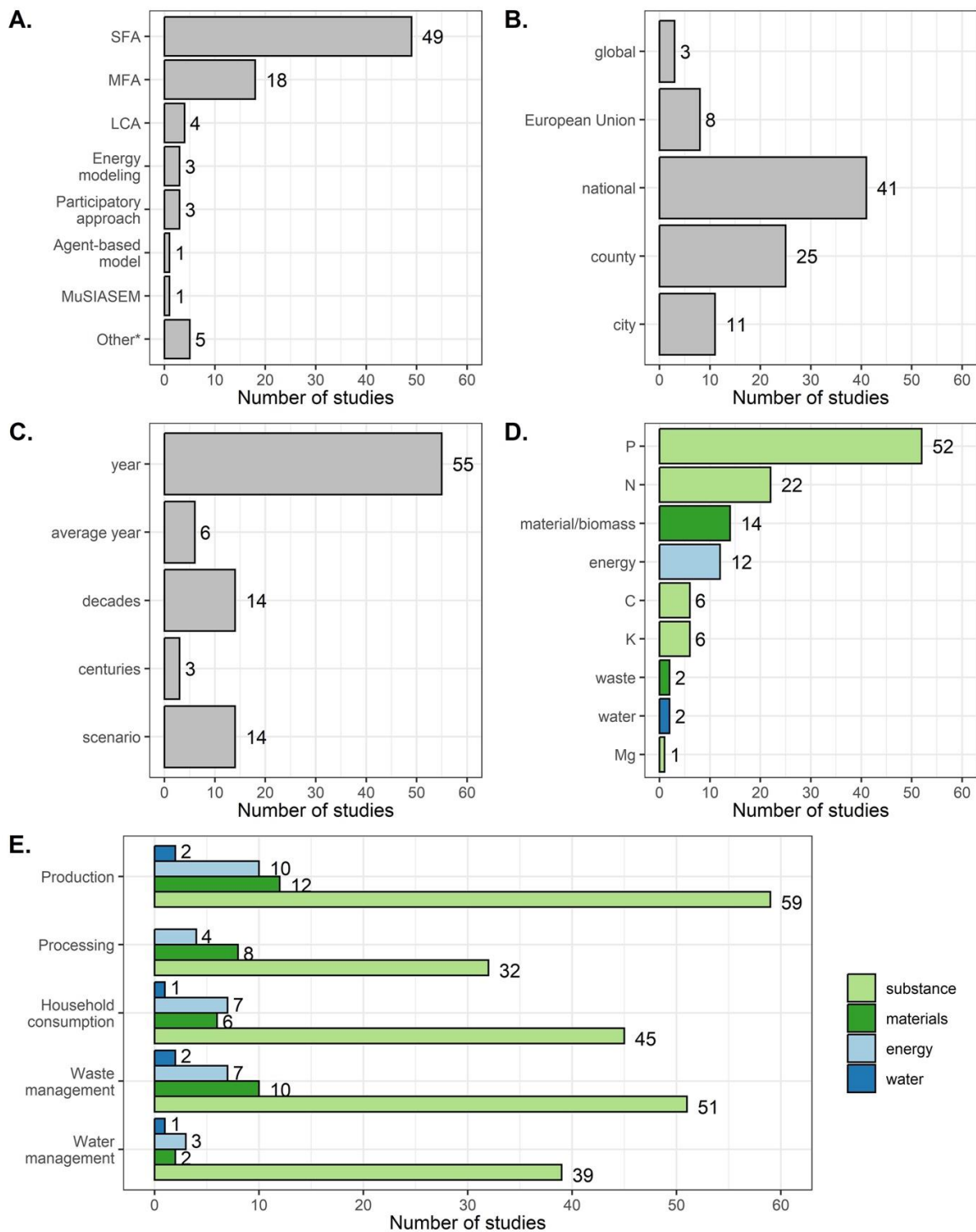
250 conversion ratios and performances) and waste and loss reduction, which are often associated
251 in definitions of circularities, such as that of van der Wiel et al. (2020). For these authors,
252 nutrient circularity corresponds to recycling of nutrients in “waste products” combined with
253 increased NUE.

254 The studies of nutrient cycling followed a gradient of approaches and objectives that ranged
255 from: (i) in-depth discussion and quantification on improved nutrient recovery (e.g. Kamal et
256 al., 2019) or waste recoverability (e.g. Verger et al., 2018) or alternative phosphorus (P)
257 resources by seizing CE opportunities (e.g. Álvarez et al., 2018) and possibly identifying their
258 main advantages and disadvantages (Keil et al., 2018) to (ii) frameworks for quantifying the
259 circularity of nutrient flows, assessing consequences of system openness for managing nutrients
260 flows, and rendering these frameworks operational in case studies (e.g. Harder et al., 2021) or
261 to (iii) improvement scenarios (e.g. Hanserud et al., 2016; Sinha et al., 2022) or optimization
262 models to identify options for closing the nutrient cycles (e.g. Klinglmair et al., 2017).

263 ***As a means:*** In the means-oriented studies, circularity or increasing efficiency was only one of
264 the means used to consider pathways towards strong sustainability of AFS and to transform the
265 AFS itself. They corresponded to the foundations of SMR, which aims to limit AFS to planetary
266 boundaries and in which CE is only one of the means to achieve this end. The feasibility of
267 changes and scenarios was usually assessed using qualitative (authors' assessment) or
268 theoretical approaches. For example, Liu et al., (2016) described the feasibility of policy levers
269 for closing P cycles (e.g. P recovery, P legacy, life-cycle P management, changes in human
270 diets, changes in feed formulation) and their corresponding temporal horizons.

271 In terms of scenarios, these studies considered more radical transformations of the AFS, such
272 as changing human diets by decreasing consumption of animal products (e.g. Papangelou et al.,
273 2021) or making organic farming practices with long and diversified crop rotations more
274 widespread (Billen et al., 2021). They also discussed the extent to which stakeholders were able

275 to adopt a transformational stance to achieve more sustainable P use (Martin-Ortega et al.,
276 2022), or the socio-technical organization and political dynamics of the scenarios (Jedelhauser
277 et al., 2018). Analysis of flow governance (e.g. Bahers and Giacchè (2019) for waste
278 management) and political-legislative interventions over time (e.g. Mehr et al., (2018) for the
279 Swiss P system since the 1980s) was also discussed in relation to circularity. Several case
280 studies highlighted the mismatch between the nutrient management practices used in AFS and
281 current and potential policies (Harseim et al., 2021; Kovanda, 2022).



282

283 **Fig 3 Overview of the 78 case studies** a. methods used, b. spatial scales, c. temporal scales, d.
 284 elements and e. compartments included. *"Other" in a. includes ascendancy analysis, allocation
 285 factors, socioecological integrated analysis and optimization methods. SFA: substance flow
 286 analysis, MFA: material flow analysis, LCA: life cycle assessment, MuSIASEM: Multi-Scale
 287 Integrated Analysis of Societal and Ecosystem Metabolism. In d. and e., the colors identify the
 288 type of flows studied: substance (N, C, P, K, Mg) in light green, materials (and biomass) in
 289 green, energy in light blue: energy and water in dark blue.

290

291 ***Methods***

292 Most case studies applied substance flow analysis (SFA) (49), followed by MFA (18) (Fig.
293 3a). The main difference between MFA and SFA is the latter's higher degree of detail and
294 complexity. SFA tends to focus on the exact pathway of a specific nutrient or pollutant in
295 compartments of the AFS. As illustrated in the MFA applied at national scales by Tanzer and
296 Rechberger (2020) or van Dijk *et al.* (2016), N flows to the environment are estimated as a
297 single aggregated flow, while the SFA of Zhang *et al.* (2022), for example, distinguished N
298 flows to the atmosphere, surface water and groundwater. Some conceptual models have been
299 developed, such as NUFER (nutrient flows in food chains, environment and resources use, for
300 MFA) (Hou *et al.*, 2015; Zheng *et al.*, 2021) and GRAFS (generalized representation of agro-
301 food systems, for SFA) (Le Noë *et al.*, 2017; Papangelou and Mathijs, 2021).

302 Only 10% of the studies examined spatially explicit nutrient flows and soil balances.
303 Nonetheless, spatial approaches must be developed to address circularity due to the local
304 environmental impacts of nutrient losses. These approaches also provide additional
305 perspectives on the logistical and energy costs of transporting material such as manure, as
306 highlighted for P in the “corn belt” of the USA (Metson *et al.*, 2016).

307

308 ***Spatial scale***

309 Overall, 59% of the case studies reviewed focused on macro scales (i.e. global, European
310 Union, national), while 41% considered intermediate territorial scales (i.e. county or city) (Fig.
311 3b). Overall, 88% of the studies focused on only one scale, while the most common pairing of
312 scales was national and county levels (Klinglmair *et al.*, 2017; Nesme *et al.*, 2015; Papangelou
313 and Mathijs, 2021; Wang *et al.*, 2022). For example, Domingues *et al.* (2019) found that intra-
314 scale analysis could help distinguish counties with nutrient surpluses from those with nutrient

315 deficits. Thus, policy-makers can decide which counties have higher priority for actions to
316 transition AFS. Similarly, the city scale helps understand relations between urban and rural
317 areas (e.g. Papangelou et al., 2020), including the specialization of territories that produce,
318 others that consume and others that are sinks for waste, and the loss of circularity between urban
319 and peri-urban areas. Studies of islands (Firmansyah et al., 2017) provided good examples of
320 the linearity of flows, such as the proportion of feed imported for livestock farming, which was
321 large and obvious. The choice of scale influences the level of organization at which circularity
322 needs to be considered (Koppelmäki et al., 2021).

323

324 *Temporal scale*

325 Overall, 65% of the studies focused on only 1 year or an average year (mean: 4.2 consecutive
326 years) (Fig. 3c). Studies that focused on 1 (average) year described a situation at a given
327 moment, as an initial step to improve it. The 14 studies with decade-long analyses sought to
328 identify major and recent transformations in systems to identify the main drivers involved, for
329 example in response to political and economic changes (e.g. Hou et al., 2015 from 1961–2010
330 in Hungary). The three studies with analyses that spanned centuries (Fan et al., 2009 and Liu et
331 al., 2016 for China or Le Noë et al., 2019 for France) provided key insights into changes in
332 socio-metabolic regimes in response to transformation of societies in their sources and uses of
333 biomass (for food and other uses) and energy (solar vs. fossil), and in the circularity in these
334 regimes. Preindustrial agriculture provides a comparative case (e.g. Fan et al., 2009; Tello et
335 al., 2016), since it was designed as closed-loop systems based mainly on biomass as a source
336 of material and energy, with strong integration of crop and livestock systems. However, only
337 three of these 14 case studies with scenarios modeled scenarios over a long time horizon and
338 assessed AFS metabolism flows by considering regulatory constraints and economic incentives
339 (Tasmeea et al., 2021; Zheng et al., 2021) or future technologies (e.g. Hanserud et al., 2016).

340

341 *Types of flows*

342 P was by far the material flow analyzed most frequently (45% of studies), followed by N (19%),
343 biomass (12%), energy (10%) and other substances (14%) (Fig. 3d). The geopolitical and
344 disruption risks of the P supply could explain this greater focus on P. Indeed, unlike industrial
345 N fertilizers, which are produced through the Haber-Bosch process using fossil fuels (Smil,
346 2001), industrial P fertilizers are derived from phosphate rock, which is a non-renewable and
347 highly vulnerable resource (Cordell and Neset, 2014). Notably, 55% of the studies considered
348 only 1 (36%) or 2 nutrients (19%, usually N and P, as illustrated by Firmansyah et al. 2017).
349 Only one of the studies, of the district of Cleves, Germany (Van der Wiel et al. 2021), assessed
350 four substances (N, P, K, C) simultaneously to specify the dynamics of each in the AFS, as an
351 initial step in assessing trade-offs in the management of these substances. The relations between
352 types of flows (e.g. between N and P or nutrients and carbon) were also rarely mentioned. Only
353 a few case studies considered the energy use or flows needed to recycle and transfer nutrients
354 among compartments (Tello et al., 2016; Adetona and Layzell, 2019).

355

356 *System boundaries and compartments*

357 The systems examined in the studies varied from agriculture as one sector of the economy
358 among others (e.g. Chen and Graedel, 2016 or Adetona and Layzell, 2019) to AFS as a set of
359 processes or compartments. Nearly 25% of the studies included the five compartments of AFS
360 (Fig. 3e). The two compartments included the least were processing and water management.
361 After production, the other two compartments - human consumption and waste management -
362 were equally important in most studies since they influence the potential to recycle flows in the
363 agri-food-waste-water system, as highlighted by van der Wiel et al. (2021). For agricultural
364 production, the most common approach was to separate crop and livestock production.

365 However, few studies distinguished cropland from grassland, or different types of livestock
366 systems. When it was done, they identified livestock compartments by the category of animal
367 (e.g. Hou et al., 2015; Gameiro et al., 2019), the type of production system (e.g. Fan et al. (2009)
368 or both (e.g. Liu et al. (2017), who distinguished grazing ruminants, non-grazing ruminants and
369 non-ruminants). This approach improves assessment of the drivers related to production of each
370 livestock category and their interactions with specific types of biomass and land use in a region.

371 **Pathways to action**

372 *Socioeconomic or political dimensions and stakeholders*

373 Although all studies stated that their results could be used to better guide policy and flow
374 management, only 25 of the 78 case studies (32%) (Table S4) considered socioeconomic or
375 political dimensions or stakeholders in the method or analysis (Table 3). Our review found that
376 7 studies established relations between flows, biophysical indicators and socioeconomic
377 variables (e.g. correlations, explanatory factors, impacts (e.g. social life cycle assessment) or
378 constraints (e.g. labor), but the analyses were based on databases, and stakeholders were not
379 considered in the methods (Bai et al., 2016; Tello et al., 2016; Cattaneo et al., 2018; Padró et
380 al., 2020; El Wali et al., 2021; Tasmeea et al., 2021). One study (Ma et al., 2012) related P-flow
381 dynamics to socioeconomic variables, going beyond databases to investigate political-
382 legislative interventions and correlations between the change in P flows and socioeconomic
383 factors.

384 Stakeholders were involved in the methods of only 16 studies. In 10 of them, stakeholders
385 helped to validate data to supplement SFA/MFA (nine studies) or to build scenarios based on
386 their beliefs and assessment of trends (Sinha et al., 2022), however, they were subsequently not
387 considered in the analysis. In four studies, investigation with stakeholders was combined with
388 analysis by including stakeholders in agent-based modeling (Fernandez-Mena et al., 2020) or

389 modeling of governance (Bahers and Giacchè, 2019; Harseim et al., 2021; Marty et al., 2022).
390 These more detailed studies of the governance of flows began to assess stakeholders' ability to
391 influence flows. In the other two studies, stakeholders were included in participatory
392 approaches to co-construct a P-vulnerability index (Nanda et al., 2020) or discuss scenarios of
393 change and how they can be achieved (Martin-Ortega et al., 2022), which is the most advanced
394 form of connection to action. The governance of flows was also analyzed by investigating only
395 political-legislative interventions (Mehr et al., 2018), by emphasizing institutional regulations
396 and the influence of public policies. Overall, stakeholders were engaged in both the methods
397 and analysis of only 5 of the 78 studies (Table 3), most of which were at the city or county
398 scale.

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414 **Table 3 Consideration of socio-economic or political dimensions and stakeholders in the**
 415 **method or analysis of the case studies reviewed**, which applied to only 25 of the 78 case
 416 studies reviewed. The other 52 case studies are represented by the hatched cell. The three gray
 417 cells indicate case studies whose stakeholders were engaged in both methods and analysis.

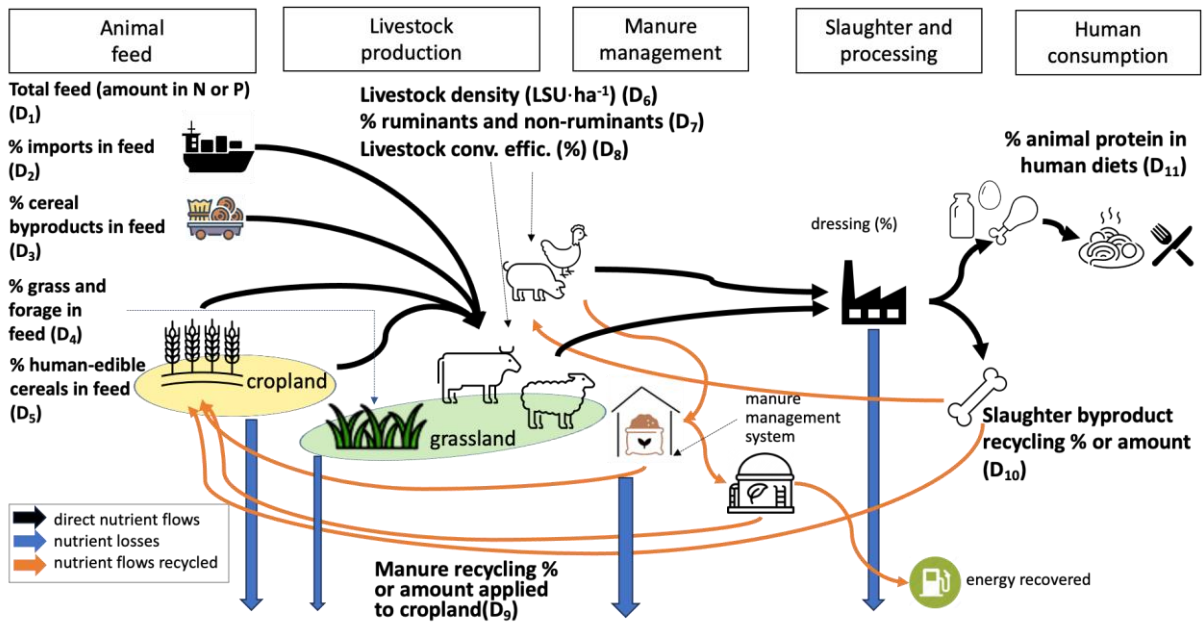
Method	Analysis					
	Relations to socioeconomic variables	Included in agent-based modeling	Governance of flows	Assessing stakeholders' potential for transformative thinking	Absent from the analysis	Total
Investigation in a political-legislative framework	1	0	1	0	0	2
Investigation with stakeholders	0	1	3	0	10	14
Participatory approach	0	0	0	1	1	2
No connection to stakeholders in the methods	7	0	0	0		7
Total	8	1	4	1	11	25

418

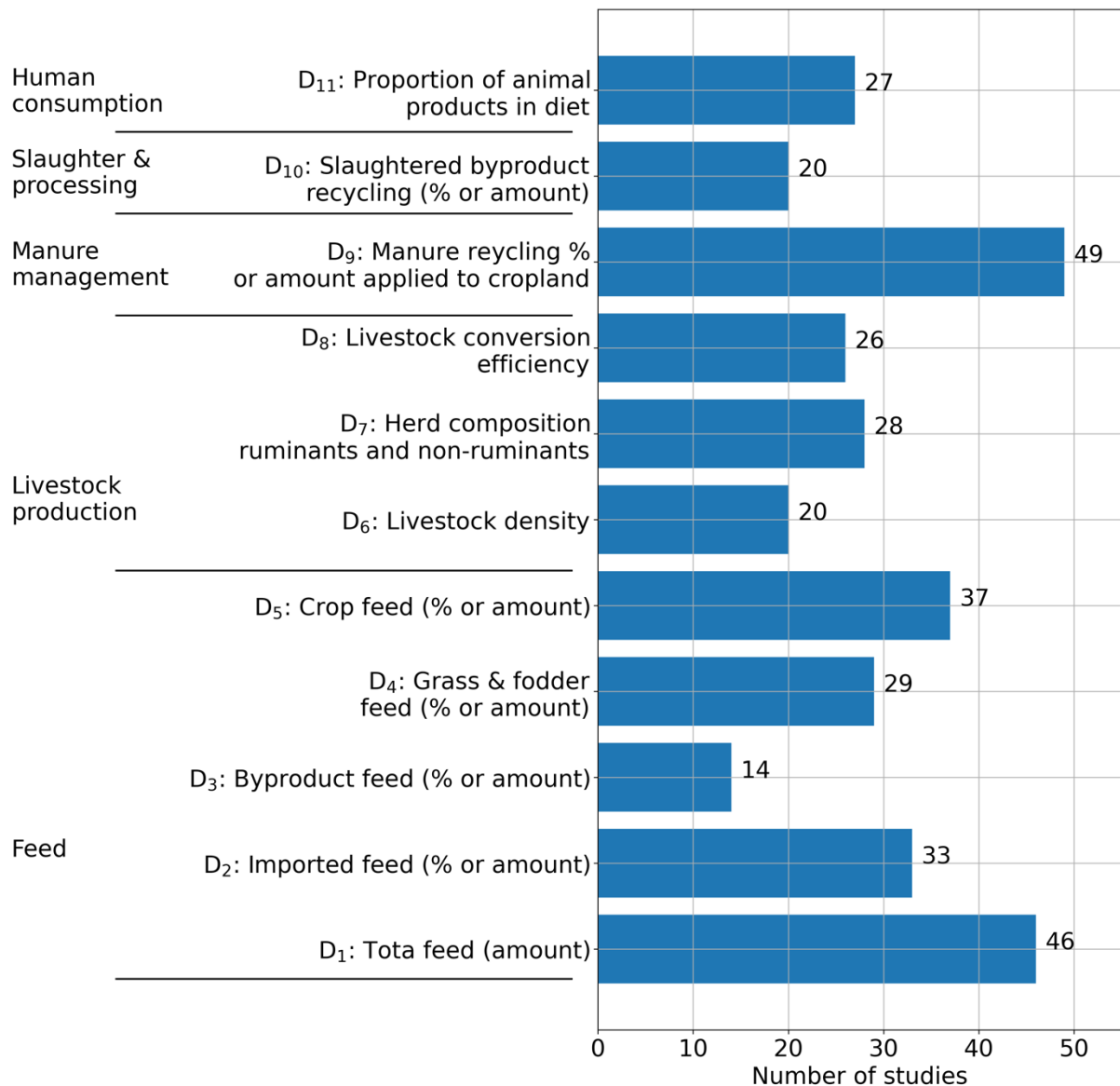
419 ***Drivers related to livestock production to change AFS metabolism and circularity***

420 Overall, 76% of the studies (Table S3-S4) considered livestock as a central component of
 421 material flows in AFS, while the remaining 24% considered aquaculture, food-side flows or
 422 waste treatment and processing as central. We identified 11 key drivers (noted D_i) related to
 423 livestock (in five compartments, from feed production to human consumption) that influence
 424 the social metabolism and circularity of AFS (Fig. 4). Notably, 90% of the studies reviewed
 425 considered at least one of these drivers. The number of these studies that examined each

426 livestock driver varied (Figure 5). On average, each study examined 4.7 drivers (range: 1 to 9).
 427 The three drivers examined most were the amount (or proportion) of manure recycled to
 428 cropland, followed by total feed and the amount (or proportion) of crops used for feed. The
 429 three drivers examined least were, in decreasing order, livestock density, the amount (or
 430 proportion) of byproducts used for feed and the amount (or proportion) of slaughter byproducts.



431
 432 **Fig 4 The 11 drivers (D_i, in bold) related to the livestock sector, examined in the case**
 433 **studies reviewed, that influence agri-food system metabolism and circularity. LSU:**
 434 **livestock units.**



435

436 **Fig 5 Number of case studies that mentioned each livestock driver identified.** The review
 437 included 78 case studies, of which 70 mentioned at least one livestock driver (D_i) and 8
 438 mentioned none (not shown).

439 **Animal feed:** in the case studies, animal feed was identified as a driver of AFS metabolism in
 440 both absolute amounts (D₁) (kt·yr⁻¹, usually of N or P) and compositions (proportions). Refining
 441 circularity required detailing feed composition as proportions of imported feed (D₂), grass and
 442 fodder (D₃), crop byproducts (D₄) and crops (D₅) (Fig. 4). Assessments of using crop
 443 byproducts for feed (Fig. 5) often lacked detail (Álvarez et al., 2018; Scherhauser et al., 2020;
 444 Martin-Ortega et al., 2022) even though they represent a way to reduce feed/food competition

445 and improve the circularity of AFS (Van Zanten et al., 2019; Muscat et al., 2021). The review
446 highlighted that feed composition (D₂ to D₅) was usually described coarsely due to a lack of
447 statistical data. For example, Zoboli et al. (2016) divided total feed into only marketable feed
448 provided by trade and industry (including imported feed) and non-marketable feed. For Europe,
449 Withers et al. (2015) indicated that dietary P intake could be decreased up to 30% without
450 decreasing livestock production, thus decreasing P in manure and P losses. For N metabolism,
451 the proportion of legumes in grass and fodder strongly influences the circularity of nutrient
452 flows (Billen et al., 2021; Marty et al., 2022) but it was rarely explored due to a lack of data on
453 permanent and temporary grassland. In contrast, studies usually quantified imported feed well,
454 and considered mainly soybeans (Withers et al., 2015). Importing feed connects local AFS to
455 abroad and usually results in opening the loops of nutrient flows (Firmansyah et al., 2017;
456 Papangelou and Mathijs, 2021; van der Wiel et al., 2021). In sum, feed is key component of
457 circularity in AFS: the larger the feed flow, the more resources are needed to increase its
458 circularity along the supply chain to decrease its environmental impacts. However, knowledge
459 of exactly how byproducts are used remains weak, which makes it more difficult to enhance
460 the role of livestock as a recycler.

461

462 ***Livestock density, composition of herds and livestock conversion efficiency:*** livestock density
463 (livestock units (LSU)·ha⁻¹) is another key driver (D₆) that influences nutrient balances of AFS
464 and the spatial variability of nutrient losses. Several studies have shown that livestock density
465 is positively correlated to industrial fertilizer use (Withers et al., 2020), the proportion of
466 imported ingredients in feed (Hou et al., 2018) and nutrient losses per hectares of agricultural
467 land (Nesme et al., 2015). Nonetheless, the studies did not always model livestock density
468 explicitly (Fig. 4). However, livestock density remains an essential mechanism in circular AFS
469 since it must be adjusted locally to the potential feed biomass available and cropland available

470 for fertilization (Hou et al., 2018; Gameiro et al., 2019; van der Wiel et al., 2021; Z. Zhang et
471 al., 2022) to minimize losses.

472 The herd composition of ruminants and non-ruminants (D_7) was detailed only in a few studies
473 (Hou et al., 2015; Liu et al., 2017; Billen et al., 2021; Cheng et al., 2022) despite the influence
474 of both types of animals on the circularity and environmental impacts of AFS (Van Zanten et
475 al., 2023). Ruminants have the ability to convert feed such as grass, which humans cannot
476 consume, into high-quality human-edible protein. But they have lower feed-conversion
477 efficiency than monogastric animals (Billen et al., 2021) and produce much more enteric
478 methane to do so. In contrast, monogastric animals require a larger proportion of grain and other
479 concentrated feedstuff that could be used as human food. Thus, compared to ruminants, they
480 have a lower carbon footprint.

481 Livestock conversion efficiency (D_8) is a driver that connects feed, manure and livestock
482 production (Bai et al., 2016; Yuan et al., 2019). Producing livestock with low conversion
483 efficiency requires focusing more on using their manure (Gameiro et al., 2019). Some studies
484 estimated livestock conversion efficiency from nutrient excretion rates, which are usually not
485 measured but based on national statistics and vary among animal categories (Papangelou and
486 Mathijs, 2021). At the national scale, weighted average livestock conversion efficiency was
487 usually set at 10-30% when expressed in P (Cooper and Carliell-Marquet, 2013; Álvarez et al.,
488 2018) or N (Z. Zhang et al., 2022), which meant that 70-90% of feed was excreted as manure,
489 which is the critical flow to recycle in AFS to minimize losses.

490

491 ***Manure management:*** manure-management systems, which drive nutrient recycling, consist
492 of multiple factors that the studies did not always describe explicitly. The proportion of manure
493 nutrients recycled or the amount applied to cropland (D_9) depends on the time that animals
494 spend in buildings and manure-management techniques (Hutchings et al., 2020). The time that

495 animals spend in buildings determines the proportion of manure theoretically recoverable. Case
496 studies usually indicated an absolute amount of manure rather than a proportion recycled on
497 cropland. The main recycling opportunities for manure addressed in the studies were N and P
498 recovery and energy generation (Keil et al., 2018). In Europe, livestock manure is the largest
499 source of recyclable P (Withers et al., 2015). The proportion of livestock manure recycled
500 influences the amount of industrial fertilizers applied on cropland and grassland (Hou et al.,
501 2018; Billen et al., 2021). Value can also be derived from manure through anaerobic digestion,
502 which produces biogas and digestate (Wu et al., 2012). In the case of some provinces of India,
503 manure is also burned as an energy source (Keil et al., 2018; Nanda et al., 2020).

504

505 ***Slaughter and processing:*** all nutrients in feed that do not end up in manure and urine become,
506 after slaughter and processing, animal products, byproducts (e.g. blood, bone, skin, head, feet)
507 or waste (Mehr et al., 2018). The proportion of byproducts recycled (D_{10}) is another driver of
508 nutrient metabolism. Dressing percentages of livestock distinguish flows of animal products
509 from those of byproducts, which have the potential to be recycled or rendered (Ferronato et al.,
510 2021), but the lack of data from slaughterhouses hinders precise quantification of the flows
511 (Amicarelli et al., 2021a, 2021b; Harder et al., 2021). Some studies examined recovery from
512 animal byproducts to produce energy, fertilizer, animal feed or pet food (Zoboli et al., 2016;
513 Prathumchai et al., 2018), depending on national safety regulations.

514

515 ***Human consumption:*** the proportion of animal products in the human diet (D_{11}) (along with
516 the human population in the region studied (X. Zhang et al., 2022)) influences feed resources
517 (Hou et al., 2015; Withers et al., 2015; Bai et al., 2016; Keil et al., 2018; Tasmeea et al., 2021;
518 Billen et al., 2021). Reducing the amount of animal proteins in human diets usually has the
519 most influence on the metabolism of AFS: it decreases absolute flows in the livestock supply

520 chain (and associated nutrient losses) with a “multiplier effect” (which is the inverse of the
521 livestock conversion efficiency) (Papangelou and Mathijs, 2021).

522

523 **Discussion**

524 **Limits of the review**

525 The review has three limits. First, systematic reviews depend on the database searched and how
526 often it is updated. For example, the study of Kleinpeter et al. (2023), which assessed the roles
527 of crops and livestock in nutrient circularity in the AFS of a tropical island, and whose subject
528 lies at the heart of our review, did not appear in our search of Scopus in March 2023, even
529 though it had appeared online in September 2022 and been published in January 2023.
530 Moreover, reviewing topics that have many definitions in the literature, such as circularity,
531 required making choices when creating search strings and selecting articles.

532 Second, the review focused on how to render circularity in AFS operational by analyzing the
533 roles of stakeholders in the studies and the drivers related to livestock production. Thus, it did
534 not focus on other key drivers, such as waste management. Nonetheless, decreasing AFS
535 metabolism and limiting AFS to planetary boundaries require systemic approaches that also
536 address recycling of biowaste and human waste. Some studies developed specific insights into
537 and knowledge of circular design for waste management, especially of food waste (Manfredi et
538 al., 2015; Donner et al., 2020).

539 Third, although analyzing trade-offs is crucial for AFS sustainability, we were unable to review
540 how SMR considers trade-offs since relatively few of the studies did so. Trade-offs between
541 nutrient flows were addressed only in the review of van der Wiel et al. (2021) and well-
542 illustrated for P and N for Austria by Tanzer et al. (2018). We argue that impacts of structural

543 changes in AFS metabolism should always be discussed in terms of multicriteria environmental,
544 economic and social dimensions.

545

546 **AFS reintegrated into territories and limited to planetary boundaries: the gaps for action**

547 Except for one case study that mentioned a potential decrease in N metabolism (Hou et al.,
548 2015) the studies that analyzed past trends mentioned an increase in AFS metabolism and loss
549 of circularity. This review highlights that all of the studies provided recommendations for
550 decreasing AFS metabolism, closing nutrient cycles and moving towards more circular
551 economies in the face of the environmental challenges.

552 Although the studies highlighted many drivers, we detailed those related to livestock
553 production, which is considered to have the highest environmental impacts in AFS. Since
554 livestock have a lower conversion efficiency than crops do (Godinot et al., 2015), changes in
555 livestock production strongly influence feed flows in AFS and management of nutrient losses
556 in manure. We also mentioned some mechanisms related either directly to the intensity and
557 circulation of flows (e.g. practices to decrease losses, improvements in technologies for
558 recovering nutrients in waste) or, less often, related to the organization of stakeholders of AFS,
559 as well as their roles and power (Withers et al., 2020).

560 However, little research has examined how to render these mechanisms and potentials
561 operational. While the SMR's potential for action is recognized (Binder, 2007), it remained
562 mainly an intention in the studies reviewed. Only one study identified socio-technical and
563 cognitive barriers to implementing change scenarios or management options: Martin-Ortega et
564 al. (2022) attempted to assess stakeholders' potential for transformative thinking. This confirms
565 that while SMR considers action important, it rarely addresses how action relates to choices of

566 socio-metabolic approaches and the use of representations in participatory approaches with
567 stakeholders (Gabriel et al., 2020).

568 Stakeholders who could influence the metabolism of AFS were rarely involved in the studies,
569 particularly economic and political stakeholders. In addition, the mechanisms mentioned act at
570 multiple organizational, political and commercial scales that go far beyond the researchers and
571 stakeholders of a territory, even though the territory is considered a relevant scale for action
572 (Papangelou and Mathijs, 2021). For example, decreasing livestock production; distributing it
573 in space as a function of the resources available to feed animals and the crops available to
574 receive manure; decreasing feed, fuel and fertilizer imports and modifying human diets involves
575 a variety of stakeholders and decision scales, which need to be coordinated.

576

577 **Three priorities for transformative socio-metabolic research**

578 *Continue to make the invisible visible*

579 The case studies highlighted changes in the transformation and looping flows of AFS in two
580 ways: opening black boxes or monitoring historical pathways. This review shows that progress
581 still needs to be made in opening the black boxes of AFS metabolism (Tello et al., 2016) from
582 a modeling perspective. For livestock in particular, few of the studies reviewed analyzed how
583 the metabolism and material flows of ruminants and non-ruminants differs. Yet these flows
584 need to be distinguished since they contribute differently to the circularity and environmental
585 impacts of AFS (Cheng et al., 2022; Harchaoui et al., 2023). More generally, SMR needs to
586 represent the diversity of production systems better; to date, they have been quantified in a
587 relatively homogeneous manner. One solution is to further combine SMR with bottom-up
588 research approaches to learn more about performances of the technologies used in farming
589 practices in order to improve material flow management. Concepts such as “manureshed”

590 (Flynn et al., 2023) have research potential by placing more focus on logistics and spatially
591 explicit analysis to rebuild nutrient circularity between regions that have too much manure and
592 others that have too little.

593 Historical pathways increase understanding of the magnitude of changes in nutrient balances of
594 AFS and only partially in drivers. Future research could concentrate on a more systematic and
595 detailed analysis of all 11 livestock drivers identified in this review and their effects on AFS
596 metabolism.

597 Opening these black boxes also means further examining the governance of flows. SMR needs
598 to develop methods to characterize the roles of multiple stakeholders in the governance and
599 management of material flows in AFS (Verger et al., 2018). SMR needs to go beyond revealing
600 hidden flows, by highlighting their cultural, social, political and technical embeddedness, to
601 better understand the socio-technical bottlenecks and power relations encountered when trying
602 to change AFS (Aubron et al., 2021; Madelrieux and Redlingshöfer, 2023). How have policies
603 and regulations changed AFS metabolism? What are the real effects of policy and public action
604 on decreasing the metabolism and increasing the circularity of AFS? Some policies have helped
605 decrease and make AFS metabolism more circular, such as the use of organic fertilizer
606 promoted by abandoning the large subsidies offered for purchasing industrial fertilizers (Bai et
607 al., 2016).

608

609 ***Engage socio-metabolic responsibility***

610 As mentioned, few case studies explicitly addressed trade-offs. Those that did addressed mainly
611 nutrient trade-offs. We argue that energy trade-offs must also be addressed. Haas et al. (2020)
612 also recommended assessing how material and energy systems interact, as well as using a
613 systemic energy perspective to avoid counterproductive effects of CE strategies. An increase in
614 circularity must not increase fossil energy use. No case studies except Papangelou et al. (2020)

615 studied energy costs associated with increasing recycling or reusing materials. Methods that
616 combine nutrient and energy analysis (Harchaoui and Chatzimpiros, 2018) must be developed
617 to consider the influence of a circular AFS on its energy use (e.g. increased nutrient cycling
618 saves the energy used to produce industrial fertilizers, but transporting nutrients from nutrient-
619 surplus regions to those in deficit needs costs energy).

620 The studies also rarely considered trade-offs between stakeholders, due to the lack of
621 considering the social dimension. Who are the winners and losers of CE strategies (Corvellec
622 et al., 2022)? In theory, crop-livestock recoupling should decrease industrial fertilizer use on
623 crop farms and excess nutrients on livestock farms. However, Regan et al (2017) found that this
624 is not always true, due to the rebound effect (i.e. Jevons paradox), which they highlighted in
625 cases of recoupling of crop and dairy production through farm cooperation. Another socio-
626 metabolic responsibility concerns the transfer of footprints (i.e. environmental damages and
627 increasing social inequalities) between territories which broadens the number of stakeholders
628 impacted. Papangelou et al. (2021) estimated an increased land footprint of European AFS due
629 to imports of food, feed, fuel and fertilizers. Future SMR should better consider externalization
630 and displacement of these footprints.

631

632 ***Engage action***

633 First, SMR should rigorously clarify concepts by positioning itself in a strong sustainability
634 perspective in which circularity is a means to remain within planetary boundaries. For example,
635 some studies reviewed considered that using byproducts contributed to CE, but doing so may
636 only represent a cascading use of resources in a linear bioeconomy (Madelrieux et al., 2023).
637 This approach should help avoid “circular washing”, especially when working with policy-
638 makers and economic stakeholders (Marrucci et al., 2022), and to use umbrella concepts to keep

639 these stakeholders from losing the focus on strong sustainability (Corvellec et al., 2022).
640 Increases in circularity should always be associated with decreases in absolute flows in AFS.
641 To effectively implement circularity in AFS and engage stakeholders in the process, both
642 technical and socioeconomic aspects of managing flows must be considered. Technical
643 solutions (e.g. integrating crop and livestock production, using manure as fertilizer, developing
644 new feed ingredients) to close nutrient cycles and decrease waste must be sustained by an
645 increase in added value for economic stakeholders (e.g. farmers, processors, consumers),
646 without overloading their work capacity. In addition, supportive policies and incentives should
647 also integrate the social, economic and cultural drivers of resource use and waste.

648 We also argue that SMR needs to develop frameworks for implementing desired scenarios and
649 transition mechanisms. They could be based, for example, on the recommendation of Liu et al.
650 (2016) to determine the feasibility and time scale of results, and that of Withers et al. (2020) on
651 collective action across the entire AFS, based on the transformational potential of all
652 stakeholders, since the burden of responsibility often lay on farmers. For Withers et al. (2020),
653 it requires examining stakeholder motives, values, “knowledge systems”, power and influence,
654 and their potential to move away from the current economic model. This goal can be achieved
655 by increasing understanding of the roles of stakeholders in AFS metabolism, as mentioned, and
656 using participatory approaches that include stakeholders as potential agents of change.
657 However, it raises questions about which research approach(es) to use and how to represent
658 AFS metabolism to engage change with stakeholders. It also raises questions about which
659 stakeholders to target and at which scales of organization to discuss and implement the
660 mechanisms of change, and how to implement cross-sectoral and multiscale discussions.
661 Should they be chosen based on their power, legitimacy or interest (Mitchell et al., 1997), their
662 transformational capacity or their potential ability to take responsibility in collective
663 governance of AFS (Withers et al., 2020)? How can SMR and representations of AFS

664 metabolism help frame and support their real transformative potentials? The field of research
665 is vast.

666 **Conclusion**

667 We reviewed 78 studies on circularity and socio-metabolic research in agri-food studies. The
668 relation between socio-metabolic research and circularity is bidirectional. Circularity can
669 provide a framework for understanding and optimizing flows in agri-food systems, and thus
670 help understand metabolic patterns of agri-food systems. In reverse, socio-metabolic research
671 can provide important insights into the intensity and technical, socioeconomic and political
672 drivers of flows in agri-food systems, and thus help identify opportunities for promoting
673 circularity as one way to reintegrate agri-food systems into territories and planetary boundaries.
674 Socio-metabolic research helps increase awareness of the metabolism of agri-food systems,
675 identify its hotspots and provide potential improvements and mechanisms of action to decrease
676 the metabolism and render it more circular in order to decrease its environmental impacts.
677 Future research should better consider stakeholders, their roles in agri-food systems
678 metabolism, potential trade-offs, the diversity of production and consumption practices, and the
679 livestock categories produced. Even with these improvements, many important steps will
680 remain to make socio-metabolic research a transformative science that truly leads to sustainable
681 agri-food systems metabolism.

682

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690

691 **Author contributions** All authors contributed to the design of the review. S.H. and M.G.
692 prepared materials and collected data. S.M.. investigated the roles of stakeholders and the
693 circularity viewpoints. SH investigated the livestock drivers. M.G. and S.H created the figures,
694 while S.M. created the tables. All authors wrote the first draft of the manuscript and approved
695 the submitted version.

696 **Declarations**

697 **Competing interests** The authors declare they have no competing interests.

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