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► **To cite this version:**

Michel-Pierre Faucon, Thierry Aussenac, Romain Debref, Stéphane Firmin, David Houben, et al.. Combining agroecology and bioeconomy to meet the societal challenges of agriculture. *Plant and Soil*, 2023, 492, pp.61-78. <10.1007/s11104-023-06294-y>. <hal-04217791>

HAL Id: hal-04217791

<https://hal.science/hal-04217791v1>

Submitted on 26 Sep 2023

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Combining agroecology and bioeconomy to meet the societal challenges of agriculture

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Abstract

Background and Aims One of the major challenges of modern agriculture is to transform agricultural systems to support food security under global change. The reduction of the agricultural carbon footprint requires the development of agroecological practices and eco-friendly processes for biomass and by-products transformation. The push towards decarbonization of several industrial sector brings about new demand for bio-based products and can constitute an opportunity for crop diversification and by-products valorisation for crop fertilization and protection. This evolution leads to the study of novel agricultural systems centered around the concept of circular bioeconomy and the development of transdisciplinary approaches combining agroecology and bioeconomy to create more resilient. But what are

27 these approaches and which steps must be taken to transform agricultural systems toward the
28 ultimate goal of sustainability?

29 *Methods* This opinion paper synthesizes such recent advances and contemporary
30 understanding of agroecology and bioeconomy synergies by focusing on 1) the agroecological
31 solutions for the bioeconomy: the ecological role of crop diversification, 2) the main eco-
32 technologies of waste recycling and biomass transformation for agroecological development,
33 3) a holistic approach of combinations of agroecology and bioeconomy for sustainable
34 agricultural systems.

35 *Results* This combination is based on the association of functional low- and high-tech
36 innovations that require life cycle analysis and a multi-assessment in cropping and farming
37 systems to decrease their energy consumption and greenhouse gas emissions.

38 *Conclusion* The combination of agroecology and circular bioeconomy constitutes an important
39 lever to mobilize in order to improve ecosystem services at the soil-plant-atmosphere interface
40 and farming sustainability at the territorial scale.

41

42 *Keywords*

43 Agroecology; bioeconomy; crop diversification; functional diversity; by-products and waste
44 recycling; agricultural systems

45

46 *Introduction*

47 One of the major challenges of modern agriculture is to transform agricultural systems to keep
48 supporting food security under global change. This requires both an adaptation to climate
49 change and its mitigation. Agriculture is not only responsible for a fourth of the total greenhouse
50 gas (GHG) emissions from anthropogenic sources (Smith et al. 2014; Bennetzen et al. 2016),
51 but also for land-use changes in the southern hemisphere that are the main cause of
52 biodiversity loss in these regions (Newbold et al. 2016). 38% of the global land surface is used
53 for agriculture and just a small part is able to support food production: only about 1,3 billion ha
54 present no strong limitation to agriculture, i.e. 10% of cultivated soils and less than 1% of the
55 global land surface (Myers et al. 2005). In spite of these limitations, the world will need to
56 produce 70 to 100% more food by 2050 if no strong regulation measures of world human
57 population growth and food waste are put in place (Lambers and Cong 2022), which is

58 predicted to lead to an additional 100 Mha being transformed into agricultural lands (Pastor et
59 al. 2019). Food security is therefore a complex issue that needs to consider all at once food
60 systems at both the global and the local scale, their many socio-economic drivers, the need
61 for sustainable energy sources and the rapid advances in agricultural science and technology
62 (Lawrence 2017).

63 Climate change affects crop yield, food prices and therefore food accessibility (Huang et al.
64 2011; Asseng et al. 2018). The increased cereal and protein crops demand from countries
65 where important limitations to agriculture exist leads to net food export from Russia, North
66 America, Europe (France, Germany, and Ukraine), Australia and Argentina and the agricultural
67 specialization of areas with high soil fertility (Lassaletta et al. 2014). This specialization
68 negatively affects the crop diversity of these areas and generates issues in crop protection,
69 weed control, sustained soil fertility and biodiversity, leading up to an increase in input use and
70 GHG emissions (Emmerson et al. 2016, Garnier et al. 2019).

71 Agriculture is however also considered as the main sector able to contribute to a sustainable
72 society based on “organic resources” as much so for biomass production as well as for genetic
73 assets (European Commission 2018; OECD 2009). Indeed, since the 1990s, the push towards
74 decarbonization of the chemical (e.g., cosmetic, pharmaceutical and food) and material
75 industries coupled with that of the energy sector brings about new demand for bio-based
76 products. Recent estimations indicated that biofuel and textile crops (i.e. non-food crops)
77 require currently about 13% of the global cropland (Poore and Nemecek 2018). As an example,
78 biomass is the most common form of renewable energy used in the European Union (estimated
79 at 60% of total renewable energy consumption by IEA, 2017), and given the current geo-
80 political turmoil, one can surmise that the demand for this source of energy will only increase
81 in the future.

82 Thus, combining the need for food security, energy independence and the important demand
83 for bio-based products constitutes a major challenge for agriculture which adds to the existing
84 difficulties that are water resources conservation, biodiversity conservation, soil and human
85 health preservation, and striving for carbon neutrality. Addressing these agro-environmental
86 issues requires to smartly combine the production of food, feed, bioenergy, fiber, and bio-
87 based chemistry in cropping systems. Our success in achieving this effort will likely determine
88 our capacity to accomplish our transition towards sustainability.

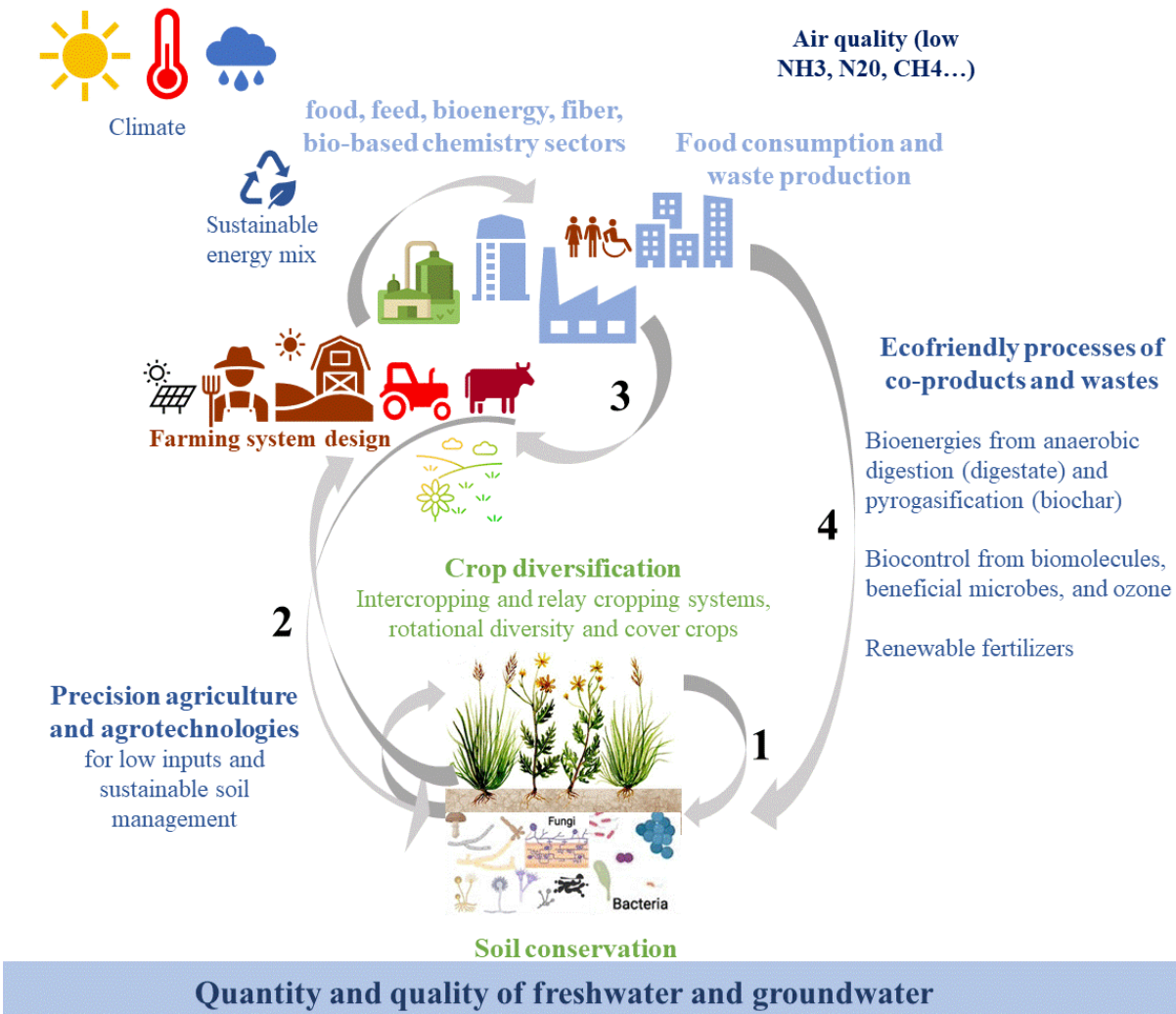
89 One strategy that has been set forth as a potential solution to these aforementioned challenges
90 is based on the concept of circularity in agricultural systems and territories, as proposed
91 through the concept of “bioeconomy” (Keswani 2021). A bioeconomy can be described as an
92 economy where the basic building blocks for materials, chemicals and energy all come from

93 renewable biological sources, mainly plant and animal sources (McCormick and Kautto 2013).
94 This economic model is compatible with the requirements for a sustainable development (both
95 environmental, economic and social) and can thus help achieve increased resilience to climate
96 change at the regional scale. The bioeconomy increases the demand for food and bio-based
97 product and therefore requires to manage the trade-offs between: 1) the expansion of
98 cultivated area to increase net agricultural productivity and 2) the search for increased yield
99 potential on already cultivated areas (Phalan et al. 2011, Stevenson et al. 2013). One key
100 component of the bioeconomy is the notion of circularity. As proposed in food systems
101 research (de Boer and Van Ittersum 2018), bioeconomy aims to reduce food and organic
102 waste, using biomass as a source of energy as well as feed, and then upcycling organic by-
103 products and wastes (manures, agri-food wastes, etc.). Livestock and anaerobic digestion for
104 biogas here play a main role as nutrient recyclers and as converters of organic matter not
105 directly suitable for food or for use as bioenergy fuel (Van Zanten et al. 2016; Paritosh et al.
106 2017).

107 In parallel, and in an effort to reduce the GHG emissions of the agricultural sector as a whole,
108 several new processes have been developed to reduce our dependence to synthetic chemical
109 solutions (Gu and Jerome 2013). The integrated production of bio-based products and energy
110 is emerging through the development of eco-efficient and robust technologies for processing
111 biomass and waste in biorefineries (Jonkman et al. 2019). These bio-based productions and
112 new processes generate several innovations for crop protection (new biomolecules for
113 biostimulation and biocontrol) and fertilization (e.g., struvite, integrated biochar-compost) (Zin
114 and Kim 2021). Although agricultural emissions increased by 1.1% annually between 2000
115 and 2010 (Tubiello et al. 2013), emissions *per unit crop* (as kg CO₂-equivalents per Gigajoule
116 crop product), have declined by more 50% in Oceania, Central & South America and in Europe
117 (Bennetzen et al. 2016). Several countries have stabilized or decreased agriculture GHG
118 emissions by reducing nitrogen (N) inputs and developing agroecological practices (Garnier et
119 al. 2019; Mrówczyńska-Kamińska et al. 2021). In this manuscript, we understand agroecology
120 through the historic definition of “the application of ecological concepts and principles to the
121 design and management of sustainable agroecosystems, or the science of sustainable
122 agriculture” (Altieri 1995; Gliessman 2013). More recently, the term has started to include a
123 more holistic approach by integrating several levels of agricultural and food systems, along
124 with a technological approach beyond farmers’ knowledge. This approach includes both low-
125 tech (i.e. agroecological processes from genetic diversity to agroecosystem functioning) and
126 functional high technologies such as innovations in precision agriculture, biocontrol, eco-
127 friendly processes of biomass transformation and upcycling based on bioeconomic
128 innovations.

129 The integration of the agroecological transition into the development of a virtuous, circular
 130 bioeconomy is a complex goal. Yet for all its complexity, the combination of bioeconomy and
 131 agroecology could also constitute a synergistic solution for further development of these new
 132 climate-smart agricultural systems. They would combine the reduction of synthetic fertilizers
 133 and pesticide inputs and more broadly promote an ecological intensification of agriculture (i.e.
 134 using natural processes to replace human-produced inputs, while maintaining or increasing
 135 food production per unit area) (Tittonell 2014). This combination of agroecology and
 136 bioeconomy has thus led to the emergence of new synergies and agroecosystems
 137 management strategies in order to achieve increased resilience. This opinion paper
 138 synthesizes such recent advances and contemporary understanding of agroecology and
 139 bioeconomy synergies (Figure 1), by highlighting: 1) the agroecological solutions for the
 140 bioeconomy: the ecological role of crop diversification, 2) the main eco-technologies of waste
 141 recycling and biomass transformation for agroecological development, 3) a holistic approach
 142 of combinations of agroecology and bioeconomy for sustainable agricultural systems.

143



144

145 **Figure 1 Combining agroecology and bioeconomy from agroecosystems to territory**

146 1. Cropping system level with the crop diversification enhanced by bioeconomy (3) and the management
147 of plant-soil interactions for a positive plant-soil feedback; 2. Farming system for nutrients recycling:
148 biomass production for feed and nutrient restitutions by manure slurry, droppings and manure; 3. Agri-
149 food system with biomass production and transformation for food, feed and bioenergy, fiber and bio-
150 based molecules and direct by-products restitution (for feed, sustainable soil management and crop
151 fertilization) 4. Agri-food system with eco-friendly processes of co-products and wastes for biocontrol
152 and renewable fertilizers production used in the cropping system for crop protection and fertilization

153

154 *1. Agroecological solutions for the bioeconomy: the ecological role of crop*
155 *diversification*

156 The principal agroecological solutions are based on the plant functional diversity services and
157 their interactions with soil biota communities and above-ground insect communities (Faucon
158 et al. 207; Tamburini et al. 2020; Dulaurent et al. 2023). Functional diversity enhances
159 ecosystem services, reduces negative environmental impacts of cropping systems and
160 enhances multiple properties and functionalities of biomass (cereal, vegetable, oilseeds,
161 protein, sugar, starch, fiber and bioenergy crops...) for various bioeconomy sectors.
162 Bioeconomy and agroecology therefore both require a crop diversification, including temporal
163 diversification (diversified crop rotations that contain three or more crops) and spatial crop
164 diversification (e.g., intercropping, relay cropping, species and/or cultivar mixture, cover crops
165 and agroforestry). These farming practices were shown to enhance ecosystem functioning
166 through yield increase and stability, higher resource-use efficiency, enhanced soil fertility,
167 reduced crop disease, and minimized environmental costs (Alletto et al. 2022; Wang et al.
168 2022). Beneficial effect of diversified crop rotations on yield and environmental aspects are
169 explained by the reduction of weed and disease pressure leading to a decrease in pesticide
170 consumption (Weisberger al. 2019; Garbelini et al. 2022). Increasing crops diversity in the
171 rotation helps reduce weeds and soil-born pathogens pressure due to improved competition
172 for resources, alternating sowing and harvesting periods, and allelopathic properties of
173 selected crops. The increase demand in plant proteins and bioenergy offers wide opportunities
174 to increase crop diversification by implanting legume species in cash crops, intercrops and
175 cover crops, or new *Brassicaceae*, *Poaceae* and *Polygonaceae* species in crop rotation
176 (Magrini et al. 2019; Marraccini et al. 2020; Kervroëdan et al. 2022). The challenge is to have
177 a good understanding of plant-soil feedback processes in order to design the crop rotation
178 sequences so as to maximise cropping systems yields and resilience against some soil-borne
179 pathogens and weeds as well as improve soil fertility (Mariotte et al. 2018).

180 Positive influence of multispecies crop mixture on yield and other ecosystem services is based
181 on ecological complementarity and facilitation between crop species. This positive effect of

182 species diversity is explained by the complementarity hypothesis among species, and more
183 specifically from their temporal and spatial niche complementarity (Yu et al. 2022). However,
184 several studies (not always published) did not show synergetic effects of functional diversity
185 on agroecosystem functioning. Positive effects of functional diversity would take place only
186 under specific environmental and agronomical conditions (e.g. in low soil fertility, low N inputs
187 and low competition conditions). Complementarity is primarily driven by the below-ground
188 biomass. Aboveground biomass of crop species can present a complementarity when light
189 competition is mitigated by appropriate sowing density and/or inter-row distance among crop
190 species. Belowground traits complementarity enhances water and nutrient acquisition by
191 different soil exploration strategies from architectural root traits (e.g., different root depths) and
192 resource partitioning from physiological root traits (e.g., using different nutrient chemical forms)
193 (Faucon et al. 2017; Montazeaud et al. 2018). Facilitation of nutrient acquisition is widely
194 demonstrated and practiced in legume/cereal intercropping. Legumes can improve N input by
195 symbiotic N₂ fixation while developing a complementary spatial root distribution to the cereal
196 crop. Besides, cereal crops can increase nodules density along legume roots, nitrogenase
197 activity and thus N₂ fixation of legumes (Ryu et al. 2020). Intercropping would improve
198 complementary N use between legumes and cereals by increasing N biological fixation by
199 legumes species and increasing N acquisition in cereals (Bedoussac et al. 2015). A recent
200 meta-analyse also showed that the proportion of N derived from N biological fixation was on
201 average 14 % higher in intercropped legumes compared to legume monocultures (Rodriguez
202 et al. 2020). Similarly, N acquisition by cereal was higher in intercropping (+61%) than in cereal
203 monocultures (Rodriguez et al. 2020). Intercropping of cereals and grain legumes represents
204 a great opportunity for improving the efficiency in using soil-derived mineral N/fertilizer N and
205 N saving by improving symbiotic N fixation in global cropping systems and constitutes a real
206 lever for GHG reduction in agriculture.

207 Facilitation of phosphorus (P) acquisition among crop species is also important to improve P
208 availability and yield benefits in multispecies crop mixture under conditions with low P supply.
209 P-mobilizing crop species (e.g., many legumes and some *Brassicaceae* species) improve P
210 acquisition for themselves and neighboring non-P-mobilizing species by releasing large
211 amounts of protons (in alkaline soils to solubilize Ca phosphate), carboxylates (to decrease P
212 sorption), or acid phosphatases or phytases which hydrolyze organic P to release inorganic P,
213 (Li et al. 2014). Interactions between belowground functional traits involved in P acquisition
214 and rhizosheath microbial communities play a pivotal role in plant P-acquisition strategies, with
215 carboxylates being key drivers of these interactions (Honvault et al. 2021). Spatial niche
216 differentiation of crop species for P acquisition is based both on P mining strategies (including
217 the interactions rhizosheath microbial communities) and P foraging capacity through

218 colonization of the soil profile and the overall total soil volume occupied by the crop (Lynch
219 2011). More than 50% of the total P losses in soils are due to water erosion (Alewell et al.
220 2020). This can be reduced in part through the use of agroecological practices (such as no-till
221 and low-till coupled with permanent or quasi-permanent soil cover) and agroecological
222 infrastructures (e.g. herbaceous hedges) (Kervroedan et al. 2021). These agroecological
223 solutions would help retain about 10 to 20 kg P. ha⁻¹, i.e. a reduction of 10 to 20 kg eqCO₂.
224 ha⁻¹, (Wood and Cowie 2004) and reduce the eutrophication risk of water bodies

225 Even if cropping systems that reduce the use of fertilizers made from non-renewable resources
226 represent one of the main levers for mitigating climate change, increased soil C sequestration
227 constitutes an ecosystem process which helps sequester additional GHG emissions for
228 agriculture decarbonization. Thus, a sound understanding of the effect of plant species
229 diversity (temporal and spatial) on organic C decomposition and stabilisation in soils has
230 become a major environmental challenge. Functional plant diversity of cropping systems plays
231 a role in C sequestration in soils (Fornara and Tilman 2008). It is explained by increased soil
232 C inputs via greater root biomass and root biomass accumulation to deeper soil horizons,
233 resulting from the presence of highly-complementary functional groups (Mueller et al. 2013).
234 Plant diversity may increase rhizosphere C input into the microbial community, leading to an
235 increased microbial activity and soil C storage. The principal increase of stable C fraction in
236 the soil is attributed in part to specific root traits of legume crops such as low C/N ratio, root
237 depth distribution, rhizodeposition, and mycorrhizal abundance (Poirier et al. 2018). Crop
238 associations and rotations including legume species are thus beneficial to C storage in soils.
239 In addition, adding cover crops to crop rotations significantly increases soil organic C by 15.5%
240 (Jian et al. 2020), and long-term intercropping may improve soil C by 4% (Cong et al. 2015).
241 Combining both the introduction of legume crops and of cover crops can thus create interesting
242 synergies in regards to soil C sequestration.

243 Cropping systems with high plant functional diversity may favour the proliferation of beneficial
244 microbes like rhizobia and arbuscular mycorrhizal fungi (AMF) which reduce disease pressure
245 via interrupting pathogens life cycles (Wang et al. 2021). Specifically, this is made possible
246 through the release of a number of molecules during root decomposition of crops that can not
247 only positively influence beneficial microbes and soil micro-fauna populations, but also hinder
248 the development of soil-borne pathogens and pests (e.g., root-knot nematodes, wireworm...)
249 (Khanal et al. 2022). In addition, these molecules released by both roots and microbes can
250 reduce the occurrence and abundance of weed species through allelopathy (Scavo et al.
251 2019). It is however difficult to specifically impute weed regulation effects to allelopathy or to
252 competition with the crop species. Further research is needed on that topic (Mahé et al. 2022).

253 Crop diversification by intercropping, relay cropping, the use of cover crops, rotational
254 diversification combining food, feed and bioenergy crops offers wide opportunities to
255 intentionally design crops functional diversity. Achieving multiple ecosystem-service goals at
256 once seems possible, notably by prioritizing pest and weed suppression and N fixation by
257 mixing legume and non-legume functional groups together (Ditzler et al. 2021). The current
258 challenge of crop diversification lies with enhancing our knowledge of crop associations with
259 legume species (cover crops, intercropping, relay cropping). Their management must be
260 improved according to cultivar selection, renewable fertilizer use, implementation of precision
261 agriculture technologies (e.g. adaptation of seed drills) and biocontrol (e.g., seed pre-treatment
262 with natural substance) in order to maximise yield and its stability while reducing GHG
263 emissions and pesticides use. The agronomic advances made possible by agroecology allow
264 for an enhancement of the agriculture decarbonization process and more globally can help
265 spread the low-input bioeconomy paradigm. Yet at the same time, bioeconomy offers new
266 agroecological opportunities through the promotion of crop diversification. A key research topic
267 in agroecology is thus to study the influence of the diversity of crop species in mixture and/or
268 in rotation combined with precision agriculture techniques, innovations in biocontrol, and the
269 use of renewable biofertilizers obtained through a circular economic model (Figure 1).

270

271 *2. Main eco-technologies of waste recycling and biomass transformation for* 272 *agroecological development*

273

274 *Circular economy of nutrients for sustainable crop fertilisation and carbon footprint reduction* 275 *of fertilizers*

276 For millennia, nutrient supply to crops relied on natural processes including soil weathering
277 and biological N fixation as well as the use of organic residuals which ensured the internal
278 recycling of nutrients. However, with the growing dependence of agriculture on fossil energy,
279 external nutrient inputs have been increasingly used to sustain an ever-growing demand for
280 food, feed and fibers (Tilman et al. 2022). Most of these biomass production systems are based
281 on the linear and inefficient utilization of global resources (Harder et al. 2021; Mikkilä et al.
282 2021). Replacing linear economic models with circular models presents excellent opportunities
283 to increase resource productivity, reduce waste and reduce dependence on primary resources.
284 In terms of nutrient return to lands, the development of circular economy aims at overcoming
285 issues related to linear economy by minimizing the depletion of resources such as phosphate
286 rocks, encouraging regenerative practices, preventing the loss of natural resources and
287 promoting the recycling of by-products and wastes (Valve et al. 2020; Muscat et al. 2021).
288 Moving toward more sustainable sources for managing nutrient in cropping systems, it is thus

289 increasingly suggested to replace fertilizers produced from or with finite resources by nutrient-
290 rich materials originating from waste material (Dawson and Hilton 2011; Faucon et al. 2015).
291 Recycling by-products such as straws, sewage sludge, animal or human excreta, anaerobic
292 digestate... or other by-products from biofuel supply chain and biopolymer/biocomposite
293 industry (e.g. chitin, chitosan) in the agroecosystems allows to enhance soil quality by
294 enriching the soil in carbon and nutrients to fertilize the crops. Some by-products can also
295 reduce the soil-borne plant pathogens under soil and climate contexts (De Caroto 2021). This
296 however implies reconnecting arable and livestock farming at farm and regional scales and
297 building new links connections between cities and their hinterlands (Muscat et al. 2021). In that
298 sense, reconnecting the places where nutrients are generated to those where they are needed
299 would allow reducing environmental damages caused by the production and use of synthetic
300 fertilizers, while preserving valuable resources (Hidalgo et al. 2021).

301 Developing a circular nutrient economy is an opportunity not only to recover nutrients from
302 waste and other by-products but more generally to create new sustainable value chains (Toop
303 et al. 2017). For instance, even though gaining insight into its effect on nutrient cycling under
304 various environment is required prior to a major upscaling, production of biochar for versatile
305 applications in agriculture and environmental sectors is increasingly regarded as an effective
306 tool to minimize waste while increasing the efficiency of circular economy (Jindo et al. 2020).
307 Biochar production through pyrolysis or gasification of biomass waste generates bio-oil and
308 syngas which can be burned to generate hot water, steam and/or turbine-generated electricity
309 while biochar may be used e.g. as a multifunctional amendment for soil to improve soil health,
310 nutrient and microbial carriers while sequestering carbon (Bolan et al. 2022). However, as for
311 other recycled materials, some challenges impede the development of a biochar based circular
312 economy at this time such as uncertainties about the relationships between biochar production
313 and its subsequent application, the difficulty to obtain homogenous biochar, the low amount of
314 field and long-term studies but also the lack of strong collaboration between researchers,
315 biochar producer and consumer, and government (Hu et al. 2021).

316 Another example of the plenty of advantages to develop circular nutrients economy is the
317 recovery of N and P in wastewater. As reviewed by Robles et al. (2020), current technologies
318 devoted to N and P recovery from wastewater include membrane-based, photosynthetic-based
319 and crystallisation-based systems. As an example, one of the most promising technologies to
320 recover P and to a lesser extent N is the production of struvite (magnesium ammonium
321 phosphate; $\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$) (Achilleos et al. 2022). Struvite can be sold and used as a slow
322 release P fertilizer, reducing resource depletion by replacing fossil-fuel based P, while its
323 production allows to alleviate P concentration in effluents and thus limits the risk of
324 eutrophication for surrounding waterbodies (Gómez-Suárez et al. 2020). Mavhungu et al.

325 (2020) report that introducing the concept of circular economy in wastewater treatment can
326 promote the sustainable management of the ever-increasing quantities of municipal
327 wastewater while addressing problems of emerging concern, such as water scarcity and
328 phosphate shortage. However, there are still some potential concerns with such approaches
329 which need to be resolved prior to wider deployment. For instance, even though struvite
330 precipitation is a fast, efficient, and environmentally friendly pre-treatment step to remove P in
331 wastewater, the environmental impacts of its recovery via the use of additional chemicals and
332 energy could not be offset by its benefits (Sena et al. 2021). The process of precipitating
333 struvite can consume a lot of energy and additional Mg needs to be added in most cases to
334 reach the optimum ratio of Mg^{2+} , NH_4^+ , and PO_4^{3-} to maximize struvite yield, which may have
335 strong environmental impacts (Fattah et al., 2022). This example shows that, even if they may
336 appear as good ideas, developing technologies to recover nutrient from waste must be fully
337 evaluated for their environmental impacts, especially using life cycle assessment (Pradel et
338 al., 2016), prior to allow their deployment at the full scale.

339 On the one hand, as acknowledged by Yuille et al. (2022), we argue that circular nutrient
340 economy is a pivotal element of clean growth but its development requires an overall strong
341 reorientation in policy, including a systemic approach, instead of working in silos with different
342 and potentially contradictory trajectories. On the other hand, it is essential to assess the
343 environmental impact of the technologies which are considered to recover nutrient from waste
344 prior to deploy them at the full scale.

345

346 *Bioeconomy of biocontrol*

347 Global food production has continuously increased during the past century to feed the growing
348 world population and led mechanically to the generation of a large amounts of food losses and
349 wastes along the food supply chain. These materials are mostly by-products of organic nature
350 originating from crop, fruit or vegetables production, oil, sugar, starch and confectionary
351 industries, grain and legume processing, distilleries and breweries which account for 140 billion
352 metric ton per year of undesired biomass (Mohlala et al. 2016). This volume of material
353 continues to grow each year with a rate of 7.5% and pose pollution and disposal problems in
354 the world caused by land degradation, greenhouse gas emissions and the widespread of toxic
355 substances (Adejumo and Adebiyi 2020; O Connor et al. 2021). The reduction of co-products
356 and wastes streams becomes a societal and environmental challenge currently addressed by
357 innovative composting and efficient recycling of products into new feedstock and components
358 for various bioeconomy sectors including food ingredients, cosmetics, nutraceuticals,
359 materials, polymers, biofuels (Tsegaye et al. 2021). Emerging waste management trends
360 consist of reusing and repurposing existing agri-food wastes as substrates for the scale up

361 production of biocontrol agents to reduce the incidence or severity of diseases caused by plant
362 pathogens and boost sustainable productivity and resilience of cultivated ecosystems (De
363 Corato 2020). Plants have evolved high biosynthetic capabilities to produce diverse secondary
364 metabolites, many of which are involved in complex defensive mechanisms against predators
365 and diseases. Number of such phytochemicals belonging to carotenoids, phenolics, flavonoids
366 families are enriched in storage organs, peel or seeds and possess a strong biological activity
367 preventing attack against various bacterial, fungal and nematode pathogens of the surrounding
368 environment (Chiocchio et al. 2023). Other classes of bioactive compounds such as alkaloids,
369 terpenoids, and volatile organic compounds (VOCs) are secreted by root and leaf tissue to
370 recruit beneficial microorganisms of the phyllosphere and rhizosphere which help stressed
371 plant to resist to infection or suppress pathogens through induced systemic resistance (ISR),
372 parasitism, antibiosis, or competition for resources or space (Lahlali et al. 2021; Pandit et al.
373 2022). Innovative biocontrol methods are based on the employment of these substances alone
374 or in mixture with efficient strains of any microorganisms that stimulate these natural
375 processes. Growing evidence indicates that efficient biocontrol solutions can be formulated
376 and produced in high yield from agricultural residues (De Corato et al. 2015; Pacifico et al.
377 2021). Plant derived wastes represent low cost, renewable, and abundant sources of valuable
378 functionalized substances, biopesticides, biofertilizers, elicitors, repellents or soil conditioners
379 which can be applied to substitute synthetic pesticides in conventional farming practices. This
380 optimal utilization of biomass produced by the agricultural and food industry in crop protection
381 sector improves profitability and valorization of agro-industrial processing chain since
382 promoting new inputs with biocontrol products for food production is an efficient way to turn
383 low quality plant materials into high added value resources. In addition, their application can
384 allow to mitigate carbon footprint attributable to the manufacturing and use of fossil chemicals
385 without sacrificing crop productivity. Several plant materials enclose soil nitrification and
386 urease inhibitors that improve nitrogenous fertilizer use efficiency through preventing loss from
387 ammonia gas and nitrite formation (Rana et al 2021; Bremmer and McCarty 2021). These new
388 crop protection products have high potential for mitigating climate change but their possible
389 contribution to field crop GHG release depends on many factors including technologies
390 employed for their production, transportation, and agricultural practices, and has to be
391 examined more in detail by Life-Cycle-Assessment” analysis. Plants wastes contain also
392 substantial amounts of carbohydrates, amino acids, minerals, and vitamins, among other
393 constituents that can be converted as nutritive ingredients for the growth of beneficial
394 microorganisms present in soil or introduced into the field following cultivation on artificial
395 media in fermenters or composts (Areeshi 2022; Kuroda et al. 2023). Many research efforts
396 made to integrate nutrient-rich wastes in fermentation processes of the biorefinery industry and
397 to develop sophisticated extraction techniques capable of selectively recovering, purifying or

398 concentrating marketable compounds have led to the successful development of numerous
399 biocontrol formulations reviewed in recent literature (Fritsch et al. 2017; Cuadrado-Osorio et
400 al. 2022; Vassileva et al. 2021). This combination of agri-food waste and innovative crop pest
401 managements not only encourages circular economy based on “zero waste” society but it
402 constitutes a real opportunity to align consumer demands, One Health and Sustainable
403 Development Goals policies guidance and environmental agenda with agroecological
404 transition acceleration toward a more virtuous food production system.

405

406 *New processes for crop protection in low inputs conditions: the use of ozone for pesticide*
407 *reduction to improve disinfection and stimulation of plant seeds*

408 For several years, the deployment of agroecological approaches with, in particular, the
409 reduction in the use of phytopharmaceutical products (insecticides, fungicides, biocides) has
410 been a major issue that impacts all plant sectors and the seed sector, in particular via the
411 "treatment" of seeds. The question of the sanitary and physiological quality of seeds therefore
412 becomes significant in order to limit the spread of plant diseases and maintain acceptable
413 production levels in an environmental context in which biotic and abiotic hazards are
414 increasingly felt. The issues related to supporting the search for alternative methods of
415 disinfection of seeds and stimulation of their germination are therefore multiple: (i) the need to
416 respond to a growing demand for “Zero treatment frequency indices seeds”, (ii) the need to
417 position itself on food markets limiting the impact on health and the environment and then, (iii)
418 the need to reduce exposure of the supply chain to plant protection products.

419 Given the general regulatory environments, the seed sector is seeing the number of solutions
420 allowing farmers to ensure the proper development of plants during the early stages (i.e.
421 germination and emergence) to be considerably reduced. In this situation, research and
422 innovation players are now striving to develop new solutions that are reliable and potentially
423 industrializable in the medium to long term. Thus, some of these alternatives are already in the
424 development phase (i.e. thermal disinfection: installations requiring significant investment and
425 very high technicality) while others are still under investigation due to the great complexity of
426 the mechanisms involved (i.e. application of bio-solutions based on microorganisms to limit the
427 development of certain pathogens and/or use in mycorrhizal preventive treatment to stimulate
428 plant development). Alongside these initiatives, the use of ozone (O₃) has already caught the
429 attention of professionals in the field of seed production and multiplication insofar as this
430 natural molecule has proven itself in many areas of disinfection and/or decontamination
431 (Brodowska et al. 2018; Sivaranjani et al. 2021) and seems to have, according to recent
432 scientific observations, particularly interesting physiological effects in the field of physiological

433 stimulation of germination and juvenile growth of the plant (Rifna et al. 2019; Pandiselvam et
434 al. 2020).

435 The first results made it possible to highlight a stimulation of the germination rate of several
436 plant species (wheat, corn, barley, peas, sunflower, tomato...), also highlighting variable
437 modifications in terms of growth of young formed organs (stems, root and leaf surface). All of
438 its observed effects are scientifically similar to the notion of "priming" (activation of biochemical
439 and molecular processes leading to germination and improves the performance of seeds and
440 young plants after sowing) already used in the international seed field. Even if the mechanisms
441 implemented here are not all precisely identified, a number of physiological hypotheses have
442 already been presented concerning the possible involvement of ozone in these reactions.
443 These hypotheses, which all refer to ROS (Reactive Oxygen Species) type inductions. It now
444 seems accepted that ROS homeostasis is strongly involved in the regulation of seed
445 germination (and dormancy breaking) giving rise to the new concept of "oxidative window for
446 germination", which limits the occurrence cellular events associated with germination at a
447 critical range of ROS level (and therefore oxidative events) (El-Maarouf-Bouteau and Bailly
448 2008; Bailly 2019). This new approach for stimulating the physiological functions of
449 germination is very promising with regard to new agroecological requirements.

450 Moreover, the potential environmental sustainability of the use of ozone in areas such as soil
451 decontamination/remediation, general crop protection, water irrigation disinfectant and, pests
452 control during grain storage are of great (Aussenac 2022). In addition to environmental
453 sustainability, economic sustainability is also important for companies employing ozone in their
454 processes (Remondino and Valdenassi 2018).

455

456 *3. Combining agroecology and bioeconomy for sustainable agrifood systems*

457 Previous paragraphs illustrate well how organizational and procedural innovations necessitate
458 systemic and structural transformations within the sociotechnical regime of agriculture. Our
459 understanding of the current innovation spreading cannot be fully conceptualized without a
460 holistic approach focused on the global transition process. The theory of transition
461 management provides valuable perspectives on how agriculture, as a sociotechnical regime,
462 can be influenced by societal challenges at various levels (Geels 2011). It reveals the
463 complexity of innovation trajectories from niche innovations to the socioeconomic landscape,
464 including geopolitical crises and climate change.

465 Today, the ecological crisis prompts policymakers to regulate the transition by combining two
466 normative elements that we find into the concept of circular bioeconomy considered as the

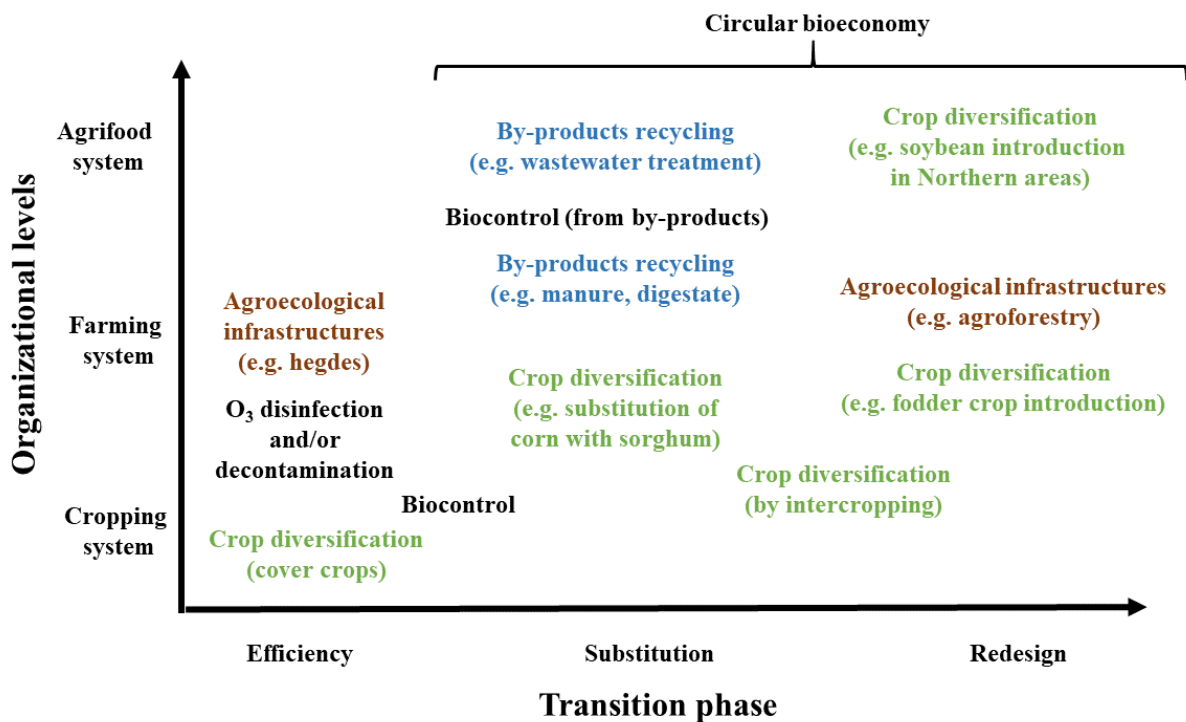
467 keystone for an ecological transition (EEA 2018). First, the integration of innovation based on
468 circular economy concepts aiming for zero waste, including by-products and waste as a
469 substitute for agrochemicals. Second, agriculture assumes a new role continuing to feed
470 humans while contributing to fossil resource substitution by producing biomass for bio-based
471 materials (Jander and Grundmann, 2019). The challenge is therefore to understand how the
472 paradigms of bioeconomy and agroecology, each with its own patterns, can be combined to
473 achieve an ecological bioeconomy: this point questions how to create new agricultural models
474 (Debref et al. 2022; Debref and Vivien 2021).

475 Several authors point out that territories are a pillar of this alliance, since territories are based
476 on peculiar production and consumption models, histories with specific regulations, local
477 resources and biodiversity, distinct geographies, and different stakeholders. Some scholars,
478 such as Girard (2022) and Lamine et al. (2019), emphasize the need for extended theoretical
479 approaches in transdisciplinary disciplines to grasp the nature of territorial innovations,
480 elaborated either from scratch or stemming from existing organizations. Agronomic science
481 illustrates this well with the landscape agronomy approach (Benoit et al. 2012). The
482 development economist Sachs also proposed the concept of ecodevelopment strategies to
483 understand societal reconfiguration considering biosphere limits (Sachs 1980; Debref and
484 Vivien 2021). Nonetheless, it appears that the concept of the bioeconomy has been defined in
485 numerous ways (Keswani 2021). In simpler terms, there exists no definitive consensus, which
486 allows for diverse interpretations, leading to inventive initiatives aligned with various intricate,
487 occasionally conflicting yet complementary forces. Consequently, the transition process
488 becomes even more intricate (Vivien et al. 2019). Finally, reconfiguring local socio-ecological
489 systems shows that diverse pathways exist, and the role played by agroecology is
490 fundamental.

491 An interesting framework which can be used to clarify the aforementioned transition process
492 from the cropping system level to higher organizational levels to the territorial level is the
493 Efficiency – Substitution – Redesign (ESR) model developed by Hill (1985). This model
494 decomposes the transition process into three non-linear steps. The *Efficiency* stage
495 corresponds to changes within conventional cropping systems aimed at reducing the use of
496 costly (both economically and environmentally) and oftentimes non-renewable inputs. In the
497 *Substitution* phase, these inputs are fully replaced by their bio-based counterparts. These two
498 stages are where agroecological practices are particularly relevant. While *Efficiency* and
499 *Substitution* are important, they are not sufficient by themselves to ensure sustainable farming
500 systems are developed. Indeed, they are additive and incremental, but they are not the most
501 transformative (Pretty 2018), as they warrant changes mostly at the cropping system or the
502 farm level. The *Redesign* phase presents social and institutional evolutions, and therefore can

503 be understood as the “transition towards bioeconomy” stage. As very few farms operate in
 504 complete autonomy with few to no linkage to the other stakeholders in their territory, this
 505 *Redesign* phase is territorial by necessity. Although the ESR model does not give any clue on
 506 how to be successful in such a transition, it can be used as a prism through which an
 507 agroecological transition trajectory can be analysed (Figure 2).

508



509 **Figure 2 Transitioning to agroecology and bioeconomy**

510 This figure illustrates how various agroecological practices also contributing to bioeconomy can be used
 511 to reach toward higher sustainability at different scales. The x-axis represents the degree of change
 512 implemented in the system, while the y-axis represents the organizational levels at which these changes
 513 are effected. Words that are color-coded identically represent the same practice type declined at various
 514 organizational levels and transition phase. Crop diversification (green), permanent agroecological
 515 infrastructures (brown), crop protection practices (black), recycling processes of by-products and wastes
 516 for crop fertilization (blue)

517

518 One of the main issues in transition processes that has been identified is the lack of markets
 519 and supply chains coordination for the farm output in agroecological systems. This has been
 520 explained in terms of socio-technical lock-in by Meynard et al. (2018) in the case of crop
 521 diversification and this situation can be easily transferred to the combination of agroecology
 522 with bioeconomy principles. These authors show that major crops in conventional agrifood
 523 systems generate their own coordination devices. These coordination devices usually range
 524 from strictly coordinated value chains, with strong coordination mechanisms of the
 525 stakeholders from upstream to downstream (i. e. production contracts), to coordination mainly

526 driven by spot markets and short-term relationships. In this configuration the socio-technical
527 lock-ins effects then refer to common and established standards, well known technological
528 solutions which constantly reinforce the system in place, leading to organizational routines
529 (Lamine et al. 2019) and higher return on investment. The arrival of new agroecological
530 practices is calling into question the balance of production models and the supply chain with
531 market segmentation. The transition process is therefore creating new competition around the
532 profit-taking.

533 In combining agroecology with bioeconomy, one must consider another level of lock-in effect,
534 at a territorial level, leading to the necessity of territorial innovations (Torre 2023). This notion
535 of territorial innovation is anchored in the fact that “the process of territorial development is
536 born of the incessant interlacing of production and governance dimensions” (...) “its dynamics
537 results from the conjunction and the combination of different development paths, with their
538 rapid advances, their blockages or even their backtracking.” (Torre 2023). For Torre (2023) the
539 territorial dynamics of transition, in agriculture, opens the way of contrasted development paths
540 which must be understood with phases of concertation, cooperation, competition or even
541 conflict, appearing at the territorial project levels. The greater the number and diversity of
542 stakeholders and the targeted objectives of each, the more complex the dynamics of the
543 territorial whole will be. New challenges are emerging, including the emergence of new
544 communities of players (e.g. farmers) aiming to become more autonomous and capture more
545 added value.

546 Several authors also developed an analysis in terms of business models or global value chains
547 as an original approach of more global territorial transitions combining bioeconomy and
548 agroecology. Indeed both agroecology and bioeconomy require transitions to innovative
549 farming practices or supply-chains (Donner and De Vries 2023; Gawel et al. 2019; Magrini et
550 al. 2019), but this deployment has its own business rationale. The deployment of the
551 bioeconomy leads to the emergence of a variety of agricultural non-food models rather than a
552 single one. Vivien et al. (2022) present the emergence of four novel agricultural models, each
553 characterized by two fundamental trade-offs. This array of agricultural models is underpinned
554 by two primary pillars.

555 The first pillar revolves around the decision regarding the transformation of the biomass
556 produced by the farmer (outsourcing versus internalization). In this context, the farmer faces
557 the choice of either internalizing the valorization process or entrusting it to a downstream
558 transformer within the sector (e.g., agribusiness) due to its significant economic influence. In
559 the former scenario, the farmer assumes the role of a mere producer, constrained to adapt to
560 the pressures exerted downstream in the sector, with limited room for transformative actions.

561 Conversely, the internalization approach grants the farmer greater autonomy, enhancing
562 adaptability and resilience.

563 The second pillar focuses on outlets and the way in which biomass is deconstructed
564 (complexity versus reductionism). Biomass can be classified into two distinct categories
565 according to its application in the bioeconomy. The first category includes biomasses that are
566 reduced to renewable carbon molecules, making it possible to replace petroleum-based
567 products. On the other hand, the second category includes biomasses that preserve their
568 inherent complexity, taking advantage of their high-value molecules and soil decontamination
569 properties. Hemp (*Cannabis sativa* subsp. *sativa*), sainfoins (*Onobrychis* sp.) and alfalfa
570 (*Medicago sativa*) are examples of such biomass.

571 Among these four models, the authors emphasize the significance of "Non-food agroecology,"
572 which intricately incorporates the farm within its broader socio-ecological framework. This
573 approach exhibits the capability to function autonomously while also exhibiting the potential to
574 synergize with other models by hybridation. These hybridations disrupt the conventional
575 paradigm of goods production, a central tenet in the prevailing socio-technical system rooted
576 in productivism. This process of transformation is catalyzing the emergence of innovative
577 coordination strategies between stakeholders, fostering a new environment for sharing skills
578 and knowledge. This change not only transform the established structure, but also encourages
579 new approaches to collaboration between diverse groups, injecting dynamism into the
580 economic landscape.

581 This point is witnessed for instance in methanization (Godard et al. 2021). In the case of
582 methanization, the coordination devices, set up at the territorial level, by farmers, are collective
583 organizations of farmers and processors. Because of this situation, the authors point out the
584 role of farmers and farmers' groups in leading the territorial transformation, with the creation
585 of a missing link between upstream and downstream activities (Berthe et al. 2022). They
586 provide a typology of farmers' motivational profile, emphasizing their key role in the social and
587 territorial dynamics needed for the emergence and success of methanization projects
588 encompassing all the stages of the methanization process. This example illustrates an
589 important aspect of this global transition: the need to consider a wide range of stakeholders,
590 mainly grounded in their proximity with the main players of the methanization¹ value chain, has
591 to be considered if one wants to overcome lock-ins. In their research, Niang et al. (2023) argue
592 that, to be successful, the territorial dynamics able to run counter to organizational routine is
593 necessary. For this to happen, the authors propose a network approach based on the "analysis

594 of the multi-stakeholder interaction relationships built and developed in a collaborative
595 environment between the stakeholders” of the territorial projects (Niang et al. 2023).

596 In the same vein, Carraresi and Broring (2021) show the shift, in the case of circular economy,
597 in business model design to foster sustainability. They suggest considering two contrasted
598 scenarios focused on the role of the focal player of the emergent or innovative value chain.
599 They suggest: “if the new recovery and release process is carried out by an incumbent, the
600 new process requires exploratory, transformative and exploitative learning together with extra
601 investments in highly specific assets and the establishment of new cross-industry relationships
602 to complement missing assets and knowledge about such technological breakthroughs
603 available on the market. If a new actor enters the emerging value chain, business model
604 innovation is mediated and moderated by a company owning both tangible and intangible
605 resources, thus catalysing technology implementation” (Carraresi and Broring 2021). As
606 innovative agroecology models are prone to create new players in the form of territorial
607 organization, the sustainability transformation leads to a redistribution of the cards of the
608 respective roles of players within agrifood systems.

609 Consequently, if one considers this topic of a combination between bioeconomy and
610 agroecology, only a few value chain types (or business models) may arise, with, for each,
611 specific value propositions, value creation and value capture which must be understood at new
612 cross sectorial linkages enabled by innovative technologies, but also thanks to news uses,
613 news valorisations and new customers.

614 Firstly, the innovative value chains may face a lack of dynamic capabilities, as showed by
615 Gaitán-Cremaschi et al. (2019). Applied social sciences approaches have brought interesting
616 insights. Considering the specific case of organic waste valuation, Girard (2023) suggest that
617 “solving (organizational aspects) requires upstream thinking about a new framework that
618 allows understanding the combined effect of horizontal organizational rearrangements at work
619 within territories, and of new inter-sectoral interactions due to the opening of new markets“.
620 (Girard, 2022:9). Optimality, in such territorial systems, is not to be found anymore in pure
621 technological or organizational solutions, but rather be done “according to territories’ features
622 (e.g. local know-how, the presence of research institutions, industrial specialization, local
623 authorities’ objectives). In particular, valorization systems must be locally grafted onto
624 agricultural, food and agri-food production systems in order to exploit their waste. For example,
625 the concentration or deconcentration of processing activities has to be done according to the
626 size of local deposits (Girard 2022). This renewed attention to the local conditions of the
627 territories, in their sociotechnical but also political (in a sense of the diversity of players’

628 intentions) dimensions, is undoubtedly at the heart of a better understanding of the challenges
629 of an efficient and sustainable combination of agroecology with the bioeconomy.

630 Another crucial aspect of these innovative combinations is the territorial scaling effects, where
631 agroecological transitions not only need to foster and develop synergies and
632 complementarities of functions and uses, but also to re-dimensionalize such functions at
633 enlarged scales, at local, regional or even larger geographical scales sometimes permitted by
634 financial devices. Ewert et al. (2023) identified, among other factors, the needs for
635 sustainability indicators across scales as a driver of this scaling up process. The combination
636 of bioeconomy and agroecology generates the need for new metrics. The challenge is not only
637 quantitative, but also qualitative. The co-design challenge, especially done in living labs,
638 between the relevant players and stakeholders at multiple levels, is a powerful driver of
639 sustainable transformation. In recent research on innovation system in sustainable
640 digitalization, Rizzo et al. (2023) focused on the important role of intermediaries in such inter
641 scales, defining the notion of floating prescriber, i.e. a duality of the roles of some stakeholders,
642 which can be at the same time players and direct prescribers of the transitions.

643 The implementation of agroecology for food and non-food uses is an alternative model
644 providing new markets and supply chain for on-farm output deriving from agro-ecological
645 transitions. At the same time, and as shown in previous paragraphs, the bioeconomy has
646 provided several useful innovations in terms of agroecological systems inputs. In both cases,
647 this potential synergistic relation can have bottlenecks. Such limitations can be found, for
648 instance, in the legal frameworks surrounding the use of biocontrol or bio-fertilisers (Caradonia
649 et al., 2019), or in the controversies raised by the concept of bioeconomy itself (Starke et al.
650 2022). But more subtle tensions, like for instance competition between uses of a certain by-
651 product or societal controversies regarding the best sustainability scenarios (Duru and
652 Thérond 2023) are also likely to appear. To alleviate these potential conflicts, we suggest that
653 the “prospective scenario” approach, a promising research tool (e.g. for instance Duru and
654 Theron 2023, on the topic of carbon neutrality), needs to be developed further.

655 Advances in agroecology are especially known for agrifood system design (Gliessman 2020),
656 but little understood and studied in agricultural systems based on an integration of the circular
657 bioeconomy through waste inclusion and by-products valorisation for crop protection and
658 fertilization, water reuse, bioenergy and biomaterials productions (Koppelmäki et al. 2019).

659

660 *Conclusion*

661 The combination of agroecology and circular bioeconomy constitutes an important issue to
662 improve ecosystem services at plant-soil-atmosphere interface and farming and territory
663 scales. It allows to mitigate climate change by the reduction of greenhouse gas emissions and
664 low inputs or the use of recycling fertilizers, and to improve the water and soil conservation by
665 pesticides consumption reduction and the use of biocontrol agent and natural molecule ozone.

666 Advances in agroecology for food system design constitute a knowledge base to study novel
667 agricultural systems based on the circular bioeconomy by including wastes (organic and
668 wastewater reuse) and by-products valorisation for crop protection and fertilization, water
669 reuse, bioenergy and biomaterials productions. This combination is based on the association
670 of functional low- and high-tech innovations that require life-cycle analysis and a multi-
671 assessment in cropping and farming systems to avoid the folly of technological solutionism
672 increasing the energy consumption and the GHG emissions. Without regulation and
673 assessment, innovations that respond to a market request, overlook physical realities and
674 unprecedented environmental rapid changes such as the depletion of resources and the
675 incompressible time of technological development. This combination requires the mobilization
676 of innovative systemic and holistic approaches, with an enlargement of circular processes at
677 territorial levels, anchored in the territories and adapted to appropriate and non-replicable
678 skills. It requires a shift in the technological models of innovation, with a strong methodological
679 background in life and earth sciences combined with the knowledge and practices of the major
680 players and stakeholders in these disruptive value chains. The main objective of this
681 interdisciplinary research would be to disentangle, within a wide range of synergies, the ones
682 which are, from an organizational and institutional perspective, the more acceptable by the
683 civil society and the more appropriable by players in place in the value chains. In other words,
684 social compromises to understand transition processes. This point underlined the need for
685 methodological innovation in order to encourage interdisciplinary scientific research and show
686 possible synergies between intertwined cycles at farming systems and bioeconomy levels. The
687 need for holistic approaches of agroecological systems at this territorial level is a key factor to
688 design sustainable agricultural systems.

689

690 *Acknowledgements*

691 The authors thank SFR Condorcet FR CNRS 3417 and UniLaSalle for “agroecology workshop”
692 organized at UniLaSalle, Beauvais, on 19 November 2021, Virginie Cendret (UniLaSalle) and
693 Gwenaëlle Lashermes (INRAE) and Olivier Pourret (UniLaSalle) for his pre-submission review
694 of the manuscript.

695

696 *Authors' contributions* all authors wrote this manuscript.

697

698 *Funding* The project was partly funded by SFR Condorcet FR CNRS 3417.

699

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