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Towards better representation of organic agriculture in life cycle assessment

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Preface

The environmental effects of agriculture and food are much discussed, with competing claims concerning the impacts of conventional and organic farming. Life cycle assessment (LCA) is the method most widely used to assess environmental impacts of agricultural products. Current LCA methodology and studies tend to favour high-input intensive agricultural systems and misrepresent less intensive agroecological systems such as organic agriculture. LCA assesses agroecological systems inadequately for three reasons: i) a lack of operational indicators for three key environmental issues, ii) a narrow perspective on functions of agricultural systems and iii) inconsistent modelling of indirect effects.

Abstract

Societal interest in the environmental performance of agricultural systems and their products is great and growing. Life cycle assessment (LCA) is the method most widely used to analyse environmental impacts of agricultural products. Current LCA methodology and studies tend to favour high-input intensive agricultural systems and misrepresent less intensive agroecological systems such as organic agriculture. This is due partly to LCA's product-based approach, which focuses on the production of biomass, without considering other ecosystem services from agricultural systems, and partly because LCA rarely considers aspects that agroecology aims to improve (soil health, biodiversity status, pesticide use impacts). The current practice of limiting consideration of indirect effects in LCA studies to indirect land use change, using economic models that ignore drivers of societal change and effects of policy instruments, further favours intensive agricultural systems. We identify three key areas (additional indicators, broader perspective, indirect effects) for which we propose recommendations and priorities for research on environmental assessment of agricultural systems.

Introduction

Societal interest in sustainable agriculture and food is great and growing^{1,2}, leading to a demand for information about the environmental performance of agricultural systems, food products and overall food

37 chains from almost all parts of society: policy makers, farmers, agribusinesses, public procurers, the media
38 and consumers. From this diverse group of stakeholders, different questions arise, such as: ‘Is product A
39 better or worse for the environment than product B? Does converting to this production system really
40 decrease environmental impacts? Should this innovative management technology be encouraged from an
41 environmental perspective?’

42

43 The method most widely used to answer such questions is life cycle assessment (LCA), whose use is now
44 well established for assessing resource depletion issues and environmental and health impacts caused by
45 production of agricultural products. LCA’s basic principle³ is to follow a product through its life cycle,
46 defining a boundary between its ‘product system’ (the ‘technosphere’) and the surrounding environment.
47 Energy and material flows crossing this boundary are related to the system’s inputs (e.g. resources) and
48 outputs (e.g. emissions to water and air). Resource consumption and pollutant emissions are then aggregated
49 into impact indicators; LCA thus focuses on negative impacts rather than including positive impacts. The first
50 LCAs were performed in the 1970s by Coca-Cola® when it investigated consequences of switching from
51 glass bottles to plastic bottles⁴. In the 1990s, application of LCA to agricultural systems began. From 1992 to
52 2018, the number of peer-reviewed English-language articles using LCA to assess agri-food systems
53 increased from 1 to 1040 per year (Fig. 1). Today, LCA is the core method in the European Union (EU)’s
54 development of a harmonised methodology for calculating environmental footprints of products (PEF)
55 including several food groups⁵.

56

57 LCAs of agricultural products very often consider only one function of an agricultural system: provision and
58 processing of biomass to produce food, fibre or bioenergy⁶. By representing agricultural systems in a limited
59 manner, this product-based approach strongly contrasts with conceptual frameworks that focus on the
60 multifunctionality of agriculture and its provision of a broad range of ecosystem services⁷ (contributions that
61 ecosystems make to human well-being). The ecosystem services concept has gained increasing global
62 recognition in policy making over the last decade, and today it is a significant research topic with diverse
63 modelling and mapping approaches at multiple spatial and temporal scales⁸. Another example of a wider
64 view of agriculture is the concept of agroecology (Fig 2), recognised by United Nations (UN) institutions as
65 a science and social movement in the transition to sustainable food systems and a pathway to achieving the
66 UN’s Sustainable Development Goals (SDGs)⁹. Organic agriculture includes many agroecological practices;
67 its umbrella organisation, IFOAM - Organics International, defines it as a ‘production system that sustains
68 the health of soils, ecosystems and people’ and ‘relies on ecological processes, biodiversity and cycles
69 adapted to local conditions’, ultimately basing it on four principles: health, ecology, fairness and care¹⁰.

70

71 Willet et al.¹ highlight the urgency of transforming global food systems to meet the SDGs and the UN’s Paris
72 climate agreement; they propose planetary boundaries for six key Earth system processes (climate change,

73 land-system change, freshwater use, nitrogen and phosphorous cycling, and biodiversity losses) on which
74 food production and consumption have great impact. There is growing agreement on the need for changes in
75 agri-food systems to make progress towards SDGs. Willet et al.¹ even call for a 'Great Food Transformation',
76 which would require appropriate assessment tools and methods to examine the environmental performance
77 of agriculture.

78
79 Here, we identify important deficiencies in LCA methodology when assessing agriculture based on
80 agroecological principles, with examples of applying it to organic agriculture. We propose ways to
81 strengthen the ability of LCA to capture environmental impacts of contrasting farming systems adequately.

82 83 **Consequences of limiting agricultural system representation**

84 LCA has a narrow perspective on functions of agriculture, linked to its product-based approach.

85 86 *Narrow perspective on functions of agriculture*

87 When analysing an agricultural system, LCA assesses its environmental impacts by considering both on-site
88 and off-site (associated with inputs) resource use, pollutant emissions and land use. LCA can capture
89 resource use and certain impacts (Fig. 3), although biodiversity losses and toxicity impacts due to pesticide
90 use are rarely included, as discussed later. Impacts are quantified using a set of indicators and reported per
91 unit of product (e.g. kg of milk or wheat); consequently, they assess eco-efficiency¹¹. In contrast, the
92 ecosystem services framework⁷ models an agricultural system differently, considering the landscape of the
93 entire farm or farming region including its semi-natural habitats such as hedges, field margins, water bodies
94 and forests. Ecosystem services are generally expressed per unit area (e.g. ha of land¹²). This framework
95 considers the supply of a broad range of services (Fig. 3) from the agricultural system: provisioning (e.g.
96 crops, livestock, water), regulating and maintenance (e.g. pest control, pollination, climate regulation) and
97 cultural (e.g. recreation, education), as well as regulating and maintenance services supplied by other
98 ecosystems to the agricultural system. However, environmental impacts associated with inputs used in the
99 agricultural system are not considered.

100
101 The frameworks of LCA and ecosystem services assessment differ greatly in how they consider land. In LCA,
102 land is an elementary resource flow modelled in the same way as fossil energy and ore resources³, while in
103 ecosystem services assessment, it is part of the agricultural system, as land is the basis for essential
104 ecosystem functions, many of which are inextricably intertwined with the soil and its functions. Furthermore,
105 LCA considers only the provision of biomass (e.g. crops, animals) from the agricultural system. With this
106 narrow focus, LCA faces obvious problems when assessing multifunctional agricultural systems, such as
107 organic agriculture, and other food systems developed within the concept of agroecology. In the scientific
108 literature, there have been many attempts to set out principles of agroecology, and a UN expert panel has

109 recently suggested a comprehensive set of 13 agroecological principles. These are organised around three
110 operational principles for sustainable food systems: i) improve resource efficiency (recycling; input
111 reduction); ii) strengthen resilience (soil health; animal health and welfare; biodiversity; synergy; economic
112 diversification) and iii) secure social equity/responsibility (co-creation of knowledge; social values and diets;
113 fairness; connectivity; land and natural resource governance; participation)⁹. Current LCA methods assess the
114 two resource efficiency principles sufficiently but consider inadequately many of the agroecological
115 principles designed to strengthen the resilience of food systems. This further illustrates the limited
116 perspective that LCA provides on food systems.

117

118 ***Product-based approach***

119 There is a large consensus that organic agriculture has lower environmental impacts per unit of land occupied
120 than conventional agriculture^{13,14}. If a farming region shifts to organic agriculture, its environmental impacts
121 will decrease (e.g. biodiversity will increase), and pesticide contamination of soil, water, air and food will
122 largely cease². Thus, government policies often favour a shift from conventional to organic agriculture. From
123 an LCA viewpoint, however, organic agriculture is not an obvious answer to environmental problems of
124 conventional agriculture, because LCA defines the function of the studied system using a ‘functional unit’,
125 which should be a precise measure of what the system delivers. Because LCAs express impacts per unit of
126 product by default, they typically identify the solutions that reduce emissions per unit of product as being the
127 best for production systems. Although organic agriculture generally emits less pollutants per unit of land
128 occupied than conventional agriculture (an area-based approach), it may have higher impacts per unit of
129 product (e.g. land occupation, eutrophication, acidification)^{13,14}, due to its lower yields per unit area. Thus,
130 focussing solely on impacts per unit of product may well result in decisions in favour of conventional
131 agriculture that may increase pollutant emissions in the farming region.

132

133 Furthermore, many consumers perceive organic food to be of higher quality in terms of nutritional quality,
134 pesticide residues and ethics, such as animal welfare¹⁵. Studies confirm organic products’ better nutritional
135 quality¹⁶ and positive effects on pesticide residues in urine¹⁷ and animal welfare¹⁸. By expressing impacts per
136 unit of product, however, LCA studies comparing organic and conventional food rarely consider product
137 quality, ignoring key qualitative aspects that are recognised in the principles of organic agriculture.

138

139 **Neglected environmental issues**

140 Surprisingly, LCA studies of agriculture and food systems rarely consider important issues such as land
141 degradation, biodiversity losses, pesticide effects and animal welfare. The last item is not strictly an
142 environmental issue, but it has recently been proposed as a fourth pillar of life cycle sustainability
143 assessment¹⁹. Although animal welfare is important, and subject to trade-offs with environmental efficiency,
144 we will not address it here.

145

146 ***Land degradation***

147 Land degradation is a serious and widespread problem, including soil-deteriorating processes such as erosion,
148 compaction, salinisation and soil organic carbon losses. Unsustainable land management in agriculture is a
149 dominant driver of land degradation²⁰.

150
151 Despite efforts over the last 15 years to improve assessment of impacts due to land use, soil properties and
152 functions remain little represented in LCA, as discussed by Vidal Legaz and colleagues when evaluating
153 models assessing impacts on soil quality²¹. The models were evaluated against criteria such as scientific
154 soundness, stakeholder acceptance, reproducibility and model applicability in LCA. The authors conclude
155 that none of the models fulfilled all of the criteria, and that trade-offs were most frequent between the
156 relevance of the impact processes modelled and the model's applicability. Of the models assessed, the
157 LANCA model was recommended for assessing land use impact in the EU PEF framework, but when
158 recently tested, it was found to still have some important limitations²². One main drawback of LANCA is that
159 it provides land use impact indicators at the coarse country scale, while soil properties have high spatial
160 variability and potential negative impacts are influenced greatly by local conditions. To favour assessment of
161 soil quality in LCA, methods need further development to strike a better balance between consideration of
162 local conditions and applicability.

163
164 A meta-analysis of 56 studies comparing a set of soil quality indicators measured in conventional and organic
165 systems shows that organic farming methods have a strong positive effect on total microbial abundance and
166 activity in agricultural soils²³. According to its definition, organic agriculture must sustain and enhance soil
167 fertility, which is considered an important output of the farming system. In most agri-food LCA studies,
168 information about human pressure on land is expressed using the simple indicator 'area of land use per
169 functional unit and year'. Thus, soil quality effects of land management practices central to organic
170 agriculture – such as diversifying crop rotations and using intercrops and catch crops – are largely ignored.
171 Consequently, current LCA studies rarely capture positive characteristics of these practices that are core
172 elements of organic agriculture.

173
174 The extent to which LCA tends to ignore impacts on soil quality can be illustrated by the fact that PestLCI²⁴,
175 the state-of-the-art simulation model used in LCA studies to estimate pesticide emissions from an
176 agricultural field to air, surface water and ground water, considers soil to be part of the technosphere. Thus,
177 in this reductive viewpoint, the soil is equivalent to other technosphere elements such as factories, electrical
178 power stations and livestock buildings. Lumping soil into the technosphere precludes assessing the toxicity
179 of pesticide residues on soil life in LCAs, which is an obvious deficiency, as the presence of pesticide
180 residues in conventional agricultural soils is the rule rather than the exception²⁵.

181

182 ***Biodiversity losses***

183 Despite repeated warnings about the rapid loss of biodiversity and mounting evidence of biodiversity's key
184 role in food security and nutrition, the ecosystems, species and within-species genetic resources of
185 agricultural systems worldwide are becoming ever less diverse²⁶. Since agriculture occupies more than one-
186 third of global land area, biodiversity losses on agricultural land are crucial. Even though intensive
187 agriculture is a main driver of certain trends in biodiversity (e.g. insect decline²⁷), LCA studies of agricultural
188 systems tend to ignore biodiversity impacts. Recent reviews of LCA studies of livestock systems²⁸ (n=173)
189 and edible oils²⁹ (n=34) reveal that less than 5% of the studies considered biodiversity impacts. Even more
190 striking, only 12% of LCA studies comparing conventional and organic agriculture considered biodiversity
191 impacts¹⁴.

192

193 Meta-analysis of many field observations has shown that organic agriculture supports biodiversity levels,
194 measured as species richness, that are approximately 30% higher than those of conventional agriculture, a
195 result that has remained robust over the last 30 years³⁰. Even future LCA studies are unlikely to capture such
196 large differences due to agricultural practices, as the method selected by the LCA community³¹ to assess
197 impacts on biodiversity (potential species loss from land use) is recommended only for identifying hotspots
198 within product systems, not for comparing products or production systems. This model thus cannot be used
199 to distinguish conventional and organic agriculture. The latest version of this model distinguishes three levels
200 of land use intensity³². A few studies (e.g. Knudsen et al.³³) provide metrics to differentiate impacts of
201 organic and conventional agriculture on biodiversity; however, an LCA-compatible method that can consider,
202 in detail, impacts of the variety of agricultural practices on biodiversity in both conventional and organic
203 agriculture is still lacking.

204

205 ***Pesticide effects***

206 Worldwide, pesticide use increased from 1.5 to 2.6 kg active ingredient per ha of cropland from 1990 to
207 2015³⁴. Pesticides are now recognised as a major driver of biodiversity loss^{26,27} in terrestrial and aquatic
208 ecosystems, and can impact human health (e.g. cancer, neurological disease)³⁵. They have caused deaths
209 from acute poisoning³⁶, especially in developing countries, and high pesticide exposure of rural populations
210 in intensive farming regions has been observed in Argentina³⁷. In many EU countries, reducing and
211 improving pesticide use to improve water quality are important policy actions, but reports of contamination
212 of surface and ground water by agrochemicals are numerous^{38,39}. Despite the negative impacts that pesticides
213 can have on humans and ecosystems, agri-food LCA studies rarely consider them. For instance, ecotoxicity
214 was considered in only 14% of 173 LCA studies of livestock systems²⁸, and toxicity-related impacts were
215 considered in only 26% of 34 studies comparing organic and conventional agriculture¹⁴.

216

217 Organic agriculture's prohibition of synthetic pesticides in order to sustain soil, ecosystem and human health
218 can be considered an application of the precautionary principle. Attempts by LCA methodology to assess

219 potential environmental and health impacts of pesticide use are laudable, but experience suggests that it may
220 take 20-30 years to discover toxicological hazards of new pesticides that had seemed relatively harmless at
221 first. For instance, when introduced in the 1970s, glyphosate-based herbicides were considered not to persist
222 in the environment and to pose low risk to non-target species. Currently, however, glyphosate has been found
223 to be widely present in the environment, probably carcinogenic to humans and a suspected endocrine
224 disruptor⁴⁰. Similarly, when introduced in the 1980s, neonicotinoid insecticides were considered to have less
225 environmental impact than the insecticides they replaced, due to the low doses used and their targeted
226 applications, such as in seed coatings. It has recently emerged, however, that neonicotinoids accumulate in
227 soils and have significant sublethal impacts on pollinators⁴¹. Furthermore, as time passes, previously
228 unknown hazards associated with pesticides are discovered, such as endocrine disruption⁴² or impacts on
229 child neurodevelopment⁴³. Consequently, as fuller understanding of environmental and health impacts of
230 pesticides may take several decades, these impacts tend to be underestimated. Furthermore, assessing
231 toxicity effects in LCAs is also limited by the lack of toxicity data for some synthetic pesticides used in
232 conventional agriculture and for some of the biological/natural and inorganic pesticides used in organic
233 agriculture¹⁴. Thus, LCA-based comparisons of toxicity effects of conventional and organic agriculture
234 remain highly uncertain.

235

236 Tukker⁴⁴ describes the underlying evaluative philosophy of LCA as a *risk assessment frame*, based on the
237 belief that knowledge about emissions and effects of substances on humans and ecosystems is adequate, that
238 emission control will work and that nature is resilient. He contrasts the risk assessment frame to a
239 *precautionary frame*, which reflects low trust in the adequacy of knowledge and in measures to control
240 emissions, and the belief that nature is fragile. Tukker proposes an LCA approach based on the precautionary
241 frame, involving indicators of the potential degree of ignorance, and the level of irreversibility of
242 contamination and effects. These indicators would be used to give a bonus/penalty score to the emission and
243 fate/effect elements that are used to calculate impacts in the traditional way. This approach may allow for
244 implementation of the precautionary principle when assessing pesticide impacts, as knowledge about
245 pesticide emissions and fate is far from complete.

246

247 **Including indirect effects of shifting to agroecological systems**

248 Attributional LCA provides information about impacts of the processes that are directly associated with a
249 product's life cycle. In contrast, consequential LCA (CLCA) considers consequences of changes in the level
250 of output of a product, including indirect effects outside the product life cycle⁴⁵. CLCA commonly relies on
251 economic models to capture relationships between demand for inputs, price elasticities, supply, etc.⁴⁶, but it
252 may also use simpler biophysical models⁴⁷. Indirect land use change (ILUC) is the indirect effect considered
253 most often in agri-food CLCAs to date, especially when studying crop-based biofuels⁴⁸. Estimates of
254 greenhouse gas (GHG) emissions due to ILUC vary widely, reflecting the high uncertainty of these models⁴⁷.
255 There is still no consensus on whether, or how, to include ILUC effects in LCA^{49,50}.

256

257 Analogous to the inclusion of ILUC GHG emissions in LCAs and carbon footprint studies of biofuels, a
258 recent LCA study assigned additional GHG emissions to organic food production, referring to consequences
259 of organic agriculture's need for more land to make up for lower yields⁵¹. Similarly, Searchinger et al.⁵²
260 defined a 'carbon opportunity cost' as the amount of carbon that would be sequestered if the additional land
261 used for organic agriculture were instead subject to natural revegetation. The justification for assigning
262 additional GHG emissions to organic food resembles the reasoning in favour of 'land sparing': by adopting
263 high-yield farming systems, we spare land for nature⁵³. Obviously, if a farmer adopts practices that increase
264 yields, less land will be needed to produce a given amount of agricultural goods. However, the land use
265 dynamics associated with shifts between higher- and lower-yielding systems are less clear. Yield gains due to
266 intensification may well increase profit in that area, thereby encouraging expansion. Therefore, land use
267 intensification may coincide with expansion of agricultural land⁵⁴. Furthermore, it is far from certain that
268 deforestation will slow down due to higher yields or that farmers will leave their land to revegetate naturally
269 in areas where agriculture is economically challenging. Instead, they may, for instance, maintain extensive
270 pasture operations in anticipation of more favourable economic conditions.

271

272 The understanding of cause-effect mechanisms of land use transitions needs to be improved. Some empirical
273 knowledge exists about how agricultural land use patterns are affected by intensification or the introduction
274 of biofuel crops. However, there is a lack of knowledge about land use consequences of agroecological food-
275 system transitions, which involve changes in both production modes and consumption patterns.
276 Consequently, cause-effect mechanisms for these transitions are even more uncertain and difficult to model.
277 Further, economic models used in many CLCAs are calibrated using historical experiences and are ill suited
278 for exploring situations in which public policies shape development towards compatibility with the Paris
279 climate agreement and SDGs, which require drastic deviation from long-term trends, possibly through
280 disruptive innovations that make established production practices obsolete.

281

282 Furthermore, a scientifically robust assessment of indirect effects cannot be limited to the (arbitrarily chosen)
283 issue of land use change⁴⁹, as other indirect effects are also likely to occur in the food system. A deficiency in
284 models used in CLCA lies in their roots in neoclassical economics, which assumes that individuals have
285 rational expectations and maximise utility⁴⁶ and excludes drivers of societal change such as ethical
286 considerations. Taking meat as an example, it is difficult, if not impossible, to foresee the overall
287 consequences in the food system of a shift in consumer demand towards more organic meat at the expense of
288 conventional meat. Animal welfare is a major ethical attribute of organic food that influences European
289 consumers' purchase decisions¹⁹. Such considerations may mean that consumers of organic food will
290 purchase fewer animal-based food products but with higher (ethical) standards. Hardly any studies of such
291 consumer behaviour exist; the few found (e.g. Baudry et al.⁵⁵) show that consumers of organic food tend to
292 eat less animal-based food and more plant-based food. Also, price effects must be included: if consumers buy

293 organic products, which are more expensive than their non-organic equivalents, they will have less money to
294 buy other polluting products or services. Such effects are difficult and uncertain to quantify and have been
295 included in very few food LCA studies⁵⁶.

296

297 To summarise, approaches that assign additional GHG emissions to organic food products, due to lower
298 yields than those of conventional food products, can be considered a way to integrate an environmental
299 concern into LCA, in line with the precautionary principle. However, translating yield differences at any
300 location into a corresponding area of natural land spared from conversion (or agricultural land available for
301 revegetation) implies an oversimplification that does not capture the complexity of geographically diverse
302 agroecological food systems. Singling out only one indirect effect when comparing farming systems and
303 food products is a poor strategy when searching for the changes required to make progress on several SDGs.
304 Furthermore, these approaches favour high-yielding intensive systems, which generally have high impacts
305 per ha for a range of environmental concerns, thus strengthening the already narrow focus of LCA on
306 provision of crop and animal products.

307

308 **Possible ways forward**

309 Meeting the SDGs requires urgent transformation of global agricultural and food systems towards
310 agroecology. Doing so requires appropriate assessment tools and methods to examine the environmental
311 performance of agricultural systems. By misrepresenting agroecological systems such as organic agriculture,
312 current LCA studies tend to favour intensive agricultural systems that produce high yields but provide fewer
313 ecosystem services overall than less intensive systems⁵⁷. LCA assesses agroecological systems inadequately
314 for three reasons: i) a lack of operational indicators for three key environmental issues, ii) a narrow
315 perspective on functions of agricultural systems and iii) inconsistent modelling of indirect effects. Thus, we
316 propose recommendations and priorities for three key areas of research on environmental assessment of
317 agricultural systems. Recommendations for LCA practitioners assessing agricultural systems are summarised
318 in Box 1.

319

320 **1) Additional indicators**

321 **Land degradation** represents one of the most urgent challenges for humanity²⁰. In the planetary boundary
322 framework, recently used to identify healthy diets and sustainable food production for the 21st century¹, soil
323 quality impacts are not considered. We call for a boundary for land degradation to be added to this
324 framework. The current modelling approach in LCA, in which soils are considered mainly as part of the
325 technosphere, thus making them equivalent to replaceable capital stocks, is inadequate. The degree to which
326 erosion, compaction, salinisation and loss of organic matter degrade soils, and the influence of agricultural
327 practices on these disturbances, is crucial information that urgently needs to be included in LCAs and other
328 frameworks for analysing agri-food systems. Methodological developments in this field should be a top
329 research priority to improve consideration of soil quality in environmental assessments⁵⁸.

330

331 The alarming **decline in biodiversity** is a major environmental challenge for food production, as changes in
332 land and sea use are its most important drivers²⁶. The limited degree to which agri-food LCA studies have
333 addressed biodiversity impacts to date is problematic, and an LCA-compatible biodiversity indicator
334 framework that can differentiate farm management practices at a fine scale is lacking. Consequently, systems
335 appear more favourable in environmental assessments as their land use decreases, even though they may
336 intensively use agrochemicals detrimental to biodiversity dimensions such as insect diversity²⁷. Ignoring
337 important intensive practices (e.g. widespread pesticide use, low crop diversity) when assessing biodiversity
338 impacts is not consistent with recent research identifying drivers of species decline^{27,59} and can lead to the
339 conclusion that land sparing is the best solution for halting biodiversity losses associated with agriculture.
340 For instance, Willet et al.¹ proposed a boundary for cropland use in future food systems without adequately
341 discussing land use intensity. There is a critical need for datasets and indicators to explicitly assess impacts
342 of farm management practices on biodiversity in environmental assessments of food and other agricultural
343 products²⁶.

344

345 Comprehensive assessment of **pesticides' negative effects** on ecosystems and humans requires detailed data
346 on amounts and characteristics of active ingredients used, application methods, crop types and development
347 stages, soil properties and climate conditions. Many of these data are insufficiently available in developed
348 countries and often lacking in many developing countries. Likewise, the dearth of information on risks to
349 farm workers' health due to working with pesticides is troublesome. While new pesticides often – but not
350 always – tend to have lower impacts than existing pesticides, their full range of impacts requires decades to
351 emerge, illustrating that knowledge about pesticide emissions, fate and effects is incomplete. Development of
352 an approach based on the precautionary frame seems an appropriate way forward. Agri-food LCA studies are
353 not alone in largely disregarding pesticide impacts; for instance, Willet et al.¹ omitted them when choosing
354 environmental indicators for guiding transformation of food systems. Given the many negative effects
355 pesticides have on humans and nature, this omission is worrying, and reveals the need for massive and broad
356 research to improve assessment of pesticides' environmental and health impacts.

357

358 Land degradation, biodiversity impacts and negative effects of pesticides are serious problems associated
359 with agricultural production. LCA studies have rarely considered these detrimental processes to date, and
360 LCA still lacks fully comprehensive indicators to quantify them when assessing food systems' environmental
361 impacts. Consequently, decision makers are currently provided unbalanced information, as trade-offs among
362 different environmental aspects are not sufficiently emphasised, leading to the obvious risk that
363 environmental assessments of food systems will fail to detect synergies in land management options.

364

365 **2) The broader perspective**

366 Because LCA was originally developed to assess environmental impacts of industrial products, it focuses on

367 reduced impacts per unit of product. When applied to agriculture, this approach tends to favour more
368 intensive systems, which have higher yields but also higher impacts per unit area. Thus, LCA studies of
369 agriculture and food implicitly advocate the land-sparing theory. This strong product-based approach,
370 however, fits poorly when assessing impacts on important ecosystem services that must be managed at the
371 landscape scale. For instance, mosaic landscapes with small fields and high crop diversity favour
372 biodiversity and key ecosystem services (e.g. crop pollination, biological pest control) while maintaining
373 agricultural productivity⁵⁹, but current LCA practice does not capture the positive effects of these landscape
374 configurations.

375

376 Furthermore, adequate assessment of agroecological systems, which are much more reliant on local
377 resources and adapted to the local context than intensive high-external-input systems, requires a fine-grained
378 approach to LCA that considers local soil, climate and ecosystem characteristics, as well as detailed
379 representation of farm management practices. These variables should be integrated in models used to create
380 LCA data. Current efforts to regionalise these data are a step in the right direction, but they need to be
381 advanced to be able to assess agroecological systems at the necessary local spatial scale.

382

383 Measuring and valuing provision of ecosystem services for a range of spatial scales is a key area of
384 innovation required to assess sustainability of food systems⁹. As current LCA methodology is not adequate to
385 assess multifunctional agricultural systems with their surrounding landscapes, we propose to integrate it with
386 other environmental assessment frameworks, such as that for ecosystem services. One example of such
387 integration is the framework recently developed by Alejandro et al.⁶⁰ for optimal coverage of ecosystem
388 services in LCA. The authors first propose a set of 15 categories of ecosystem services derived from the
389 CICES classification method that provide optimal coverage. They then identify which of these categories are
390 assessed in the widely used ReCiPe2016 LCA method. They finally prioritize missing categories, resulting in
391 a ranking of ecosystem service categories to be included in LCA, to help guide the research community.

392

393 Overall performance of agricultural systems is complex to measure and model. Because most ecosystem
394 services associated with agricultural production depend on the context (mostly at the farm and/or landscape
395 scale), it is critical to assess them at a fine spatial resolution. For this, we call for dedicated research efforts.

396

397 **3) Indirect effects**

398 Analysing and comparing contrasting farming systems (e.g. conventional vs. organic agriculture) requires
399 complex information about factors such as changes in food consumption patterns, practices that may increase
400 yields, use of crop residues and waste, and how much marginal land is used. Modelling consequences of
401 conversion to less intensive agricultural systems requires a comprehensive food-system perspective rather
402 than addressing only yield levels and potential ILUC GHG emissions. Meaningful quantification of ILUC
403 and other indirect effects requires that we improve our knowledge about how drivers of societal change, and

404 policy instruments, may affect consequences of shifting from conventional to organic food. More systems-
405 based research is needed on factors governing land use change, dietary transitions (conventional to organic,
406 as well as shifts towards more plant-based diets) and reduced food waste to spare land and reduce pressures
407 on resource use and ecosystems⁶¹. Science and policy efforts should concentrate on real-world solutions,
408 such as increasing yields of agroecological systems and halting deforestation through improved land and
409 forest governance^{62,63}, rather than on quantifying ILUC factors.

410

411 **Conclusion**

412 Food production is one of the largest drivers of global environmental change and thus a major cause of
413 exceeding planetary boundaries. Transformative redesign of agri-food systems based on agroecological
414 principles is urgently needed, but it requires appropriate assessment tools and methods to examine the
415 environmental performance of these systems. Currently, LCA misrepresents agroecological systems such as
416 organic agriculture, partly because its product-based approach focuses by default on the output of
417 provisioning services from agricultural systems, and partly because key aspects of sustainable agriculture
418 (better soil health, lower biodiversity impacts, lower pesticide use impacts) are largely ignored. Consequently,
419 LCA studies tend to favour intensive high-input agricultural systems that produce higher yields but provide
420 fewer ecosystem services overall than less intensive systems. Environmental assessment of agricultural
421 systems must adopt a broader perspective, consider negative impacts of pesticides and consider effects of
422 agricultural practices on soil health and biodiversity. In addition, more research is needed to allow for
423 meaningful modelling of ILUC and other indirect effects.

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- 568

569

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577

Competing interests

578 The authors declare no competing interests.

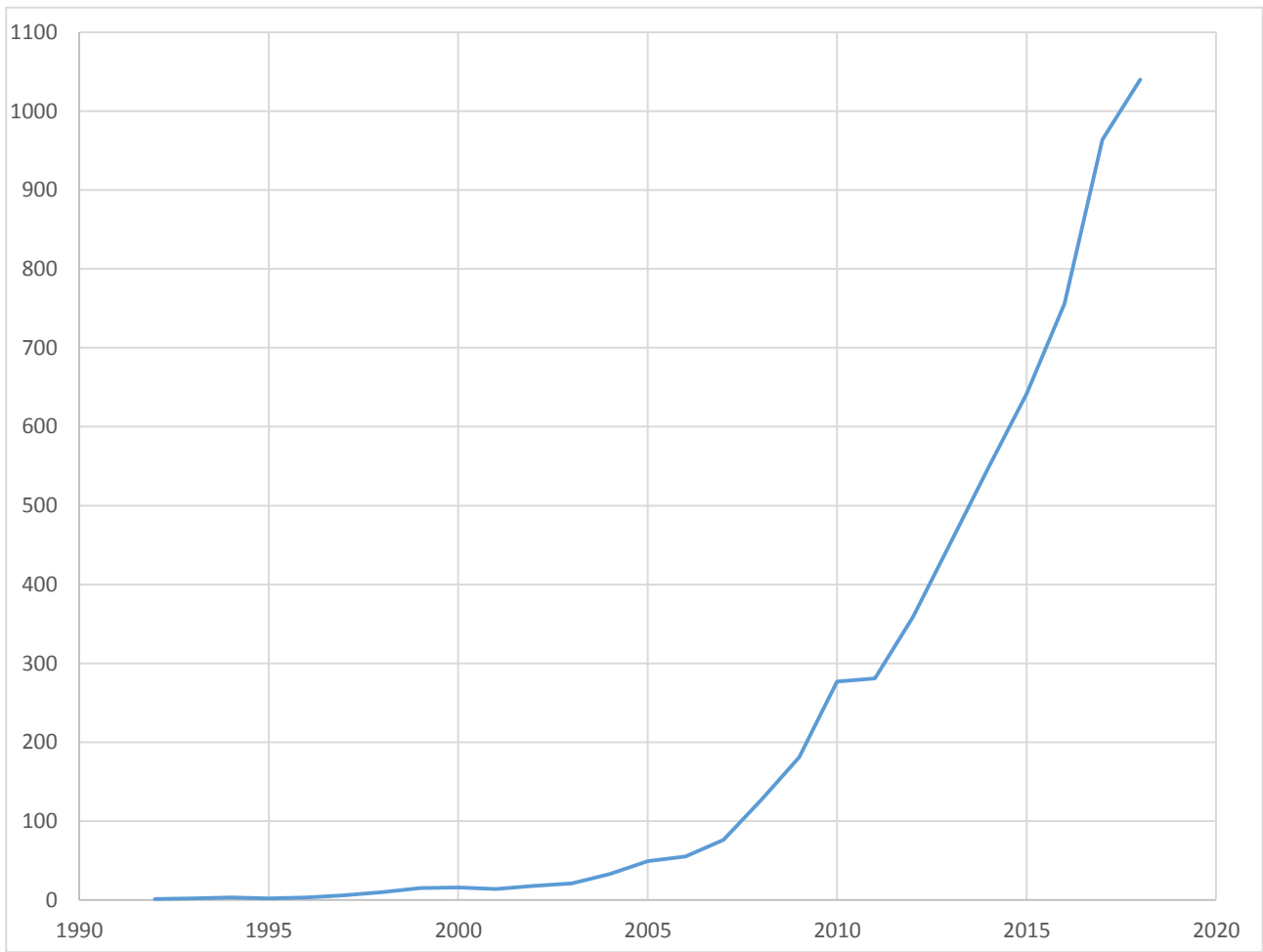
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Additional information

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588 Figure 1. Annual number of peer-reviewed English-language articles published from 1990-2018 using life
589 cycle assessment to assess agricultural and food systems (total = 5954).

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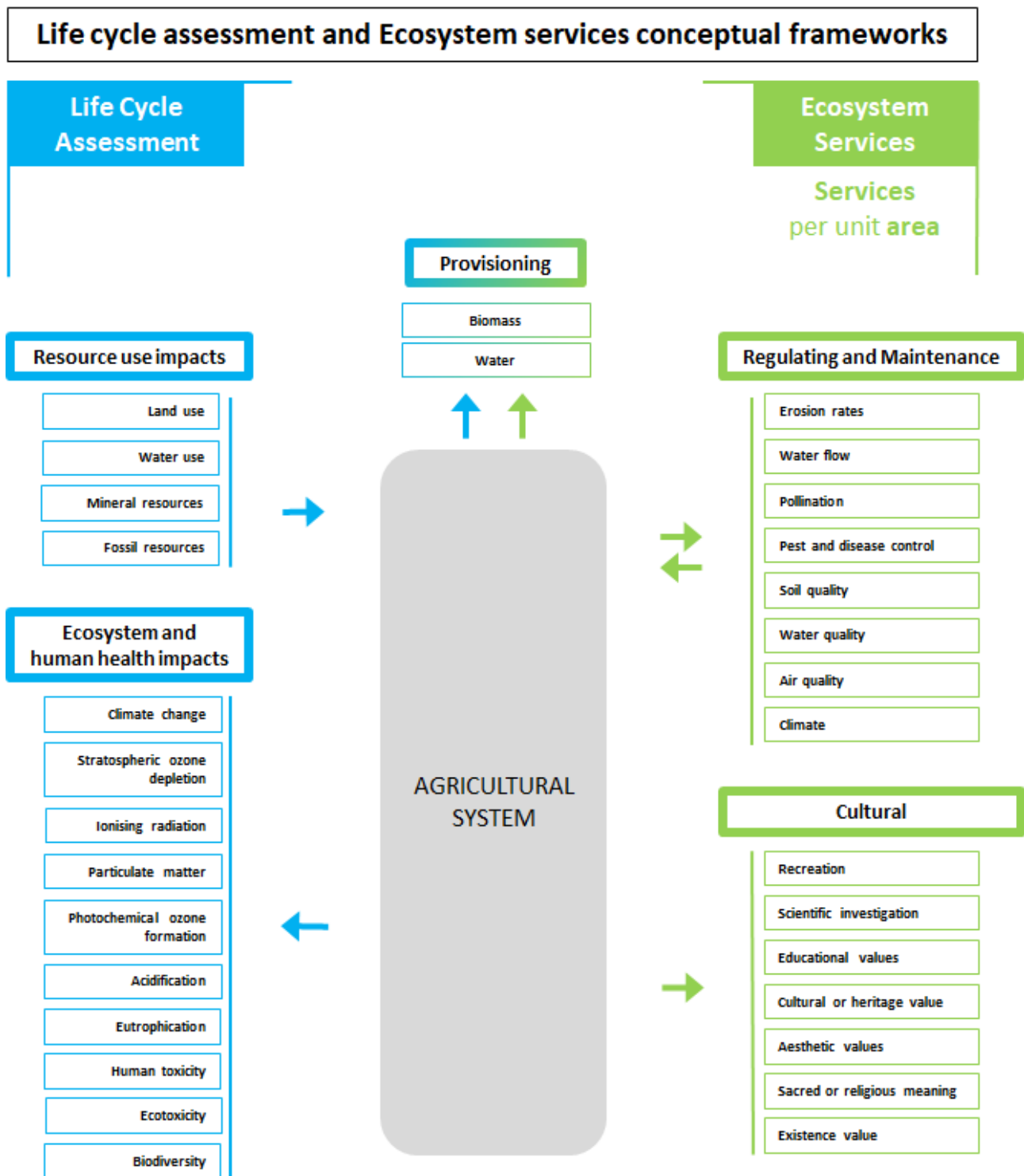
592

a)

b)

593 Fig 2. Agricultural systems and landscapes can be classified along a continuum from high-input intensive to
594 agroecological. Photo a) shows an example of high-input intensive agriculture, aiming for high yields of a
595 few crop species, with large fields and no semi-natural habitats. Photo b) shows an example of
596 agroecological agriculture, supplying a range of ecosystem services not limited to crop and animal
597 production, relying on biodiversity and crop and animal diversity instead of external inputs, and integrating
598 plant and animal production, with smaller fields and presence of semi-natural habitats. Current LCA
599 methodology and studies tend to favour high-input intensive agricultural systems and misrepresent less
600 intensive agroecological systems such as organic agriculture.

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Figure 3. Life cycle assessment (LCA, in blue) and ecosystem services (in green) conceptual frameworks. The central panel represents an agricultural system, i.e. a farm or farming region, including semi-natural habitats. LCA assesses environmental impacts of the system by considering both on-site and off-site (associated with inputs) resource use, pollutant emissions and land use. Resource use, ecosystem and human health impacts are quantified using a set of indicators expressed per unit of product (e.g. kg of milk produced). Ecosystem services assess provisioning, regulating and maintenance, and cultural ecosystem

610 services provided by the structure and functions of the system. Other ecosystems supply the system with
611 additional regulating and maintenance ecosystem services. Ecosystem services are quantified using a set of
612 indicators expressed per unit area, e.g. ha of land occupied. LCA and ecosystem services have common
613 ground, e.g. emissions and sequestration of greenhouse gases are considered in the climate change impact
614 (LCA) and in the climate regulating service (ecosystem services). This comparison also reveals “blind spots”:
615 LCA does not consider ecosystem services other than provisioning, whereas ecosystem services do not
616 consider resource use and effects of inputs used in the system.
617

618 ***Box 1. Recommendations for LCA practitioners assessing agricultural systems.***

- Assess land degradation, biodiversity and pesticide effects, and do so using the best methods available.
- Use both product-based and area-based functional units.
- Supplement LCA with other frameworks, such as that for ecosystem services, for more comprehensive analysis of functions of agricultural systems.
- Consider farm practices and local soil, climate and ecosystem characteristics in detail.
- When studying indirect effects of transition to agroecological systems, do not consider only indirect land use change.
- If indirect effects are included, results should be interpreted very carefully because of the high uncertainty.

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