



Chapter six - transformation of agricultural landscapes in the Anthropocene: nature's contributions to people, agriculture and food security

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3 **Transformation of agricultural landscapes in the Anthropocene:**
4 **Nature’s contributions to people, agriculture and food security.**

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61 Abstract

62

63 Multiple anthropogenic challenges threaten nature's contributions to human well-being. Agricultural
64 expansion and conventional intensification are degrading biodiversity and ecosystem functions,
65 thereby undermining the natural foundations on which agriculture is itself built. Averting the worst
66 effects of global environmental change and assuring ecosystem benefits, requires a transformation of
67 agriculture. Alternative agricultural systems to conventional intensification exist, ranging from
68 adjustments to efficiency (e.g., sustainable intensification) to a redesign (e.g., ecological
69 intensification, climate smart agriculture) of the farm management system. These alternatives vary in
70 their reliance on nature or technology, the level of systemic change required to operate, and impacts
71 on biodiversity, landscapes and agricultural production. Different socio-economic, ecological and
72 political settings mean there is no universal solution, instead there are a suite of interoperable
73 practices that can be adapted to different contexts to maximise efficiency, sustainability and
74 resilience. Social, economic, technological and demographic issues will influence the form of
75 sustainable agriculture and effects on landscapes and biodiversity. These include: 1) the socio-
76 technical-ecological architecture of agricultural and food systems and trends such as urbanisation in
77 affecting the mode of production, diets, lifestyles and attitudes; 2) emerging technologies, such as
78 gene editing, synthetic biology and 3D bio-printing of meat; and 3) the scale or state of the existing
79 farm system, especially pertinent for smallholder agriculture. Agricultural transformation will require
80 multifunctional landscape planning with cross-sectoral and participatory management to avoid
81 unintended consequences and ultimately depends on people's capacity to accept new ways of
82 operating in response to the current environmental crisis.

83

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85 *nature's contributions to people, ecosystem services, nature-based solutions, sustainability.*

86

88 **1. Introduction**

89 Nature provides multiple and diverse contributions, including biodiversity and ecosystem goods and
90 services, to the support and well-being of the global human population (Díaz et al., 2018; IPBES,
91 2019; Potts et al., 2016). At the same time, marking the shift towards a new epoch, the Anthropocene
92 (Ellis et al., 2010; Steffen et al., 2011), the Earth is undergoing rapid anthropogenic environmental
93 challenges, including climate change, modification or degradation of ecosystems and a global
94 biodiversity extinction crisis (IPBES, 2019; IPCC, 2019). These changes constitute a planetary-scale
95 crisis due to the growing erosion or elimination of nature and its contributions to well-being, such as
96 stable ecosystem functioning, nutritional security and provision of clean air and water, food and
97 energy (Chaplin-Kramer et al., 2019; Dirzo et al., 2014; IPBES, 2019; McGill et al., 2015; Potts et
98 al., 2016; Wall et al., 2015).

99 A suite of interacting, socio-cultural and economic drivers directly and indirectly modifies the
100 supply of ecosystem goods and services from nature (IPBES, 2016; IPBES, 2019). Globally, the
101 human population is projected to grow to 9.7 billion up to 2050 until plateauing around 11 billion in
102 2100 (UN, 2019). In addition, increased per capita consumption alongside continuing income and
103 economic inequality within and across world regions is expected. Following such a trajectory will
104 risk further environmental degradation and a failure to meet current and future policy objectives, such
105 as the Sustainable Development Goals of the 2030 Agenda for Sustainable Development, the Aichi
106 Biodiversity Targets and the CBD post-2020 Global Biodiversity Framework, aiming at improving
107 human well-being and preserving the biosphere (CBD, 2014; IPBES, 2019; UN, 2015).

108 Land-use change is consistently the principal direct driver of changes in habitat cover on
109 approximately half of the Earth's terrestrial surface (Ellis et al., 2010; Foley et al., 2005; IPBES,
110 2019; Newbold et al., 2016). The interplay between land-use (e.g., natural resource extraction, habitat
111 conversion and food production) and the state and processes of the natural ecosystem (e.g.,
112 geomorphology, climate, biological functions) form landscapes. Of the many environmental goods

113 that humans obtain from nature, agriculture and the production of food continues to be the major
114 factor shaping the world's landscapes (IPBES, 2019; IPCC, 2019). For example, as of 2017 the total
115 production of cereal crops had increased 240 % relative to the 1961 baseline (IPCC, 2019) driven by
116 a combination of high-yielding crop varieties, intensive management, and arable land expansion at
117 the expense of semi-natural habitats (Ellis et al., 2010; Foley et al., 2005; IPBES, 2019).

118 Agricultural expansion and habitat conversion is the most widespread form of land-use
119 change, and coupled to conventional intensive agricultural management, currently represents the
120 main approach to assuring food supply (2016; IPBES, 2019). Conventional intensive agriculture is
121 the prevailing food production paradigm and is characterised by industrial management of livestock
122 or large-scale monocultures with high external inputs and mechanisation that circumvent many of the
123 ecosystem limits to production (Godfray et al., 2010; Kovács-Hostyánszki et al., 2017; Pretty, 2018).
124 In this manner, conventional intensive management and agricultural expansion has been profoundly
125 successful at delivering increased yields and food security (Godfray et al., 2010; Piesse and Thirtle,
126 2010; Pretty, 2018; Qaim, 2017); although significant nutritional deficits and asymmetries in access
127 to food remain in large parts of the world marked by structural poverty (IPBES, 2019; Willett et al.,
128 2019).

129 The appropriation of up to 50% the Earth's land-surface for cropping or livestock production
130 (Ellis et al., 2010; IPBES, 2019) (**Fig. 1**), has altered landscapes, and is the predominant pressure on
131 biodiversity and environmental goods and services supporting human well-being (Aizen et al., 2019;
132 IPBES, 2019; Newbold et al., 2016; Potts et al., 2016). This reliance of agriculture on beneficial
133 biodiversity and ecosystem processes and the fact that this socio-cultural and industrial practice is
134 itself a major cause of ecosystem degradation and biodiversity extinction, means that agricultural
135 reform is a necessity for shaping future food production, landscape structure, and societal responses
136 to the current environmental crisis.

137 *[insert Figure 1]*

138 A societal consensus is emerging that to forestall the worst effects of global environmental
139 change, while continuing to feed a growing and economically developing human population,
140 transformative and systemic changes are required to move to a sustainable agricultural management
141 (Bommarco et al., 2013; Godfray et al., 2010; IPBES, 2019; Kleijn et al., 2019; Pretty, 2018;
142 Rockstrom et al., 2017; Tittone, 2014). The world is a heterogeneous place ecologically, socio-
143 culturally and economically but there are evident risks of “biotic homogenization” (IPBES, 2019).
144 Assuring food and nutritional security whilst restoring and maintaining ecological and ecosystem
145 functioning will require a suite of options that deliver these objectives in the most optimal and socially
146 just way for particular geographical, socioecological, and societal contexts and scales (Godfray et al.,
147 2010; IPBES, 2019; Rockstrom et al., 2017; Tittone, 2014).

148 There is an array of technological and farming approaches, available or developing, that might
149 assure the stability of agricultural production whilst meeting the challenge of moving to a sustainable
150 food system. These include farm management approaches that differ according to their dependence
151 on existing or emerging technologies – e.g. precision agriculture (Pretty, 2018; Pretty, 1997; Wolfert
152 et al., 2017), genetic modification (Altpeter et al., 2016; Chen et al., 2019; Ort et al., 2015), synthetic
153 biology and alternative proteins (Mattick et al., 2012; Mouat et al., 2019; Stephens, 2013) – or in
154 harnessing knowledge about natural ecosystem processes in support of agricultural production
155 (Bommarco et al., 2013; Garibaldi et al., 2019; Kleijn et al., 2019; Rockstrom et al., 2017). Such
156 changes in the agricultural system will also depend on the farmers’ socio-cultural and institutional
157 context, capacity or willingness to adapt, and trade-offs between their worldviews and those of other
158 societal actors (Marshall et al., 2014; Martin et al., 2018; Moser and Ekstrom, 2010; Vermeulen et
159 al., 2018). The form that a sustainable agriculture takes will also be influenced by the socio-economic
160 scale and ecological state of the existing agricultural system (Hill et al., 2019; Lowder et al., 2019;
161 Zimmerer et al., 2015) and the social and environmental changes precipitated by increasing
162 urbanisation worldwide (Horst et al., 2017; IPBES, 2019; Orsini et al., 2013). Therefore, the choice
163 between adopting either nature-based farm management or agri-technological solutions has profound

164 socio-ecological considerations and implications for future sustainable landscapes, biodiversity and
165 the balance of ecosystem services and disservices they provide (**Fig. 2**).

166 *[insert Figure. 2]*

167 In this chapter, we outline the indirect drivers that create contemporary agricultural landscapes
168 [Section 2.0]. We then discuss the ways that contemporary agricultural systems form landscapes and
169 shape ecosystem services and disservices [3.0]. Next, we discuss alternative models of agriculture
170 being debated, advocated, developed or implemented as part of current efforts to improve agricultural
171 sustainability [4.0]. We then examine some key issues that influence the transition to a sustainable
172 agriculture: the social dimensions of transformative changes in agriculture and food system
173 sustainability [5.0] using the example of urbanisation [5.1.1], emerging technologies for novel crops
174 and foods [5.2] and the economic scale and ecological state of the farming system [5.3]. We conclude
175 with a discussion of how nature-based, technological or policy responses could profoundly change
176 how the world obtains food and nutrition and the consequences for the crisis in biodiversity and
177 ecosystem function [6.0].

178 **2. Indirect drivers of change in contemporary agricultural landscapes**

179 Agricultural landscapes are the product of the interplay between multiple, mostly anthropogenic,
180 drivers that directly (proximate causes) or indirectly (underlying causes) influence the composition
181 and distribution of land-use. Because agriculture is both a societal and industrial practice, agricultural
182 landscape structure is impacted indirectly by demographic, sociocultural, economic, technological
183 and institutional factors governing food production (IPBES, 2019). Over the last 50 years, the
184 growing human population coupled to policies and technological advances that have facilitated rapid
185 economic growth and globalised trade and commerce have profoundly altered consumption and
186 production patterns at all scales (Godfray et al., 2010; IPBES, 2019; Qaim, 2017). This complex
187 interaction among these underlying conditions has led, in many regions of the world, to agricultural
188 expansion and the adoption of conventional, intensive agricultural management, either to feed

189 regional populations or to produce commodities for geographically distant markets on a global scale
190 (Godfray et al., 2010; IPBES, 2019). This widespread shift to an industrial agriculture has tripled
191 global agricultural crop production since 1970, which alongside globalised trade in agricultural
192 commodities and products, has produced substantial economic gains, but also with costs of
193 biodiversity loss and highly modified and simplified landscapes (Godfray et al., 2010; IPBES, 2019;
194 Piesse and Thirtle, 2010; Pretty, 2018).

195 Urbanisation is another major social, economic and demographic trend with consequences for
196 the structure and function of agricultural landscapes. Currently, urban land only represents 1% of the
197 habitable land (**Fig. 1**), but urbanisation of the human population is predicted to increase globally,
198 especially in parts of Africa and Asia that are some of the world's most productive croplands
199 (d'Amour et al., 2017; IPBES, 2019). Urbanisation brings risks and opportunities for agriculture,
200 ecosystems and landscapes [5.1.1]. It creates challenges for the production and distribution of food
201 and livelihood instability in already vulnerable regions of the world (IPBES, 2019). Urbanisation also
202 distances the human population from the site and process of food production altering social and
203 ethical attitudes pertaining to farming and the use or preservation of nature. It creates a societal debate
204 over which modes of agriculture or food production [see section 4.0] can or should be adopted, the
205 dietary expectations or choices of people, and, according to their social and economic acceptability,
206 where the site of different forms of food production should be located [5.1.1]. Such changes to the
207 human lifestyles and population distribution coupled to the need for climate change adaptation [4.3.2]
208 raise the prospect of profound changes in land-use that overlap with the potential for land sparing
209 (**Grass et al. this volume**), rewilding and restoration of biodiversity and good ecosystem functioning
210 (IPBES, 2019; Navarro and Pereira, 2012; Tscharntke et al., 2012).

211 Another crucial dimension that shapes farming, landscape structure and ecosystems is the
212 capacity and willingness of farmers to adapt to changes in the environment, economy and social
213 expectations by altering the goal or location of their activity (Moser and Ekstrom, 2010; Vermeulen
214 et al., 2018). Those farmer decisions depend on technical or market considerations, and are also

215 deeply embedded in farmer identity (Marshall et al., 2014) and the wider agricultural, institutional
216 and economic contexts that create opportunities, incentives or limitations to adaptation (Dowd et al.,
217 2014; Martin et al., 2018; Park et al., 2012; Vermeulen et al., 2018). Farmer decisions, incorporating
218 their views and priorities on farming practices, the environment, social norms and their roles and
219 responsibilities may conflict with other actors such as urban dwellers, authorities or other rural
220 inhabitants (Mann and Jeanneaux, 2009) (see Skrimizea et al. this volume). Considering the social
221 (including economic) dimensions of agriculture are therefore central to the transformation to a
222 sustainable agricultural system and the future structure and functioning of the landscape [5.0].

223 **3. Agriculture: a direct driver of landscape structure, biodiversity and** 224 **ecosystem services**

225 Conventional intensive agricultural management is itself a multifactorial direct driver of change in
226 biodiversity and ecosystem function (IPBES, 2019; Potts et al., 2016). Through the industrial-scale
227 management of livestock and large-scale monocultures in simplified rotations reliant on high levels
228 of agrichemicals (synthetic fertilisers, insecticides, herbicides, fungicides), this type of farm
229 management homogenises landscape habitat structure to produce a highly simplified ecosystem
230 (Garibaldi et al., 2017; Kovács-Hostyánszki et al., 2017). Aside from habitat loss, further impacts on
231 non-target biota occur through the impacts of agrichemicals, both in terms of direct (e.g. toxic and
232 sub-lethal effects of pesticides) and indirect effects (ecological community shifts elicited by
233 herbicides) (Chagnon et al., 2015; Godfray et al., 2014; Kovács-Hostyánszki et al., 2017; Pisa et al.,
234 2015). In this manner, the effects of conventional intensive agriculture act as an environmental filter
235 leading to the homogenisation of biological communities by extirpating many species and
236 interactions. Only those species with traits that pre-adapt them to exploit (e.g., r-selected insects,
237 resistant biotypes) or tolerate (e.g., mobile, generalist omnivore) the highly anthropogenic farmed
238 landscape persist (Bommarco et al., 2010; Burkle et al., 2013; Dainese et al., 2019; de Vries et al.,

239 2013; IPBES, 2019; Marini et al., 2014; Martin et al., 2019; Redhead et al., 2018; Tsiafouli et al.,
240 2015; Wall et al., 2015).

241 These effects of agricultural expansion and conventional intensive management have directly
242 impacted the organisms that provide services underpinning crop production itself – namely
243 pollination, pest regulation and a number of soil services (Chaplin-Kramer et al., 2019; Dainese et
244 al., 2019; Potts et al., 2016; Tscharntke et al., 2012; Wall et al., 2015) (**Fig. 3**).

245 Pollinators are one important example of how functional groups of organisms can help to
246 safeguard crop yields and wild plant reproduction (Potts et al., 2016). Managed pollinators, such as
247 the western honeybee, are important providers of pollination services for certain plant taxa or in
248 already highly intensified systems (Hung et al., 2018; Potts et al., 2016; Rollin and Garibaldi, 2019;
249 Woodcock et al., 2013). Complete reliance on one or a small number of managed pollinators for crop
250 pollination is risky, however, due to the threats from pests and pathogens causing bee diseases (Potts
251 et al., 2016; Vanbergen et al., 2018) and mismatches in supply and demand that may create pollination
252 deficits (Breeze et al., 2014). However, wild pollinators have been shown to be important crop flower
253 visitors (Hung et al., 2018; Potts et al., 2016; Rader et al., 2016) that safeguard fruit set even in the
254 presence of managed bees (Garibaldi et al., 2013). Most crop pollination is provided by a small
255 number of dominant (i.e., highly abundant) species (Dainese et al., 2019; Kleijn et al., 2015; Winfree
256 et al., 2015). Diverse pollinator communities, however, usually better support crop pollination and
257 crop quality (Aizen et al. this volume) through species complementarity over space or time and among
258 crop species (Brittain et al., 2013; Dainese et al., 2019; Greenleaf and Kremen, 2006; Hoehn et al.,
259 2008; Winfree et al., 2018; Woodcock et al., 2019). This may be due to ‘response diversity’ -
260 differential responses to the same environmental perturbations - which increases the overall stability
261 of the pollination service in the face of environmental variability or global change (Martin et al.,
262 2019; Winfree and Kremen, 2009). Alternatively, it may be because diverse wild pollinator
263 assemblages elevate or facilitate cross-pollination rates via greater overall activity or behavioural or

264 functional complementarity arising from species trait diversity (Brittain et al., 2013; Garibaldi et al.,
265 2015; Garibaldi et al., 2013; Hoehn et al., 2008; Woodcock et al., 2013).

266 In a similar way, the abundance or diversity of natural enemies, such as predatory or parasitic
267 arthropods, can indirectly support crop production by suppressing populations of invertebrate pests
268 (Letourneau et al., 2009; Liere et al., 2015; Redlich et al., 2018; Shackelford et al., 2013). Biodiversity
269 is also key to a healthy and functioning soil. Plant-soil biota interactions, abundance of key soil
270 functional groups, and soil food web complexity are all directly linked to the delivery and resilience
271 of soil ecosystem functions underpinning plant/crop productivity (Bender et al., 2016; Blouin et al.,
272 2013; de Vries et al., 2013; Lange et al., 2015; Philippot et al., 2013; Wagg et al., 2014). Conventional
273 intensive agriculture is a major pressure on these soil biodiversity-function relationships and can lead
274 to their degradation and loss (de Vries et al., 2013; IPBES, 2019; Tsiafouli et al., 2015) with major
275 implications for soil ecosystems, crop production and ultimately human health (Bender et al., 2016;
276 Wall et al., 2015). Retaining both above-and below-ground biodiversity, particularly of functionally
277 complementary species, in a farm system or agricultural landscape provides direct and indirect
278 benefits to crop production.

279 *[insert Figure 3]*

280 It is well known that the presence of natural areas or landscape heterogeneity is fundamental
281 to supporting species diversity delivering ecosystem services in agricultural landscapes (Landis,
282 2017) and that habitat and landscape simplification under agricultural expansion erode this diversity
283 and functionality (**Fig. 3**) (Dainese et al., 2019; IPBES, 2019; Newbold et al., 2016; Potts et al., 2016).
284 For example, up to 50% of the negative effects of landscape simplification on ecosystem services is
285 due to species richness losses of service-providing organisms. This includes negative consequences
286 on crop yields (Dainese et al., 2019) and pollination and pest control by insects declines at increasing
287 distances from non-cropped areas (Garibaldi et al., 2011; Woodcock et al., 2016). Increased land
288 cover heterogeneity at field, farm or landscape scales can lead to increases in pollinator and natural
289 enemy abundance as well as pollination and pest regulation (Batáry et al., 2011; Hass et al., 2018;

290 Klein et al., 2012; Ricketts et al., 2008; Rundlöf et al., 2008; Rusch et al., 2016) (**Fig. 3**). These
291 benefits are not universal, however, and the responses of pests and enemies to land cover often vary
292 among organisms, across geographic regions, and between landscape and field management contexts
293 (Gagic et al., 2017; Gallé et al., 2019; Karp et al., 2018). In a global synthesis of natural biocontrol,
294 the landscape composition (% non-crop habitat) was a significant predictor of pest and enemy
295 abundance, predation rate, crop damage and yields, but positive and negative responses were
296 observed across studies with no consistent overall trend (Karp et al., 2018). Therefore, as non-crop
297 habitat does not always enhance biological control or other ecosystem services linked to biodiversity,
298 more information about its modulation by agricultural contexts (see **Petit et al this volume**) is needed
299 to understand the reliability of habitat conservation as a pest-suppression strategy.

300 The configuration and arrangement of non-cropped areas in the landscape is now emerging as
301 the potential key to effectively managing land to maintain natural biocontrol and pollination in
302 agricultural landscapes. Complex landscapes with smaller and/or irregularly shaped fields and habitat
303 patches have a high density of habitat edges. Such configurations of ecotones increase the probability
304 of exchange of populations and ecosystem services between crop fields and non-crop habitat (**Fig. 3**).
305 For example, a landscape-scale analysis of wild bees and butterflies in Europe showed that pollinator
306 assemblage evenness was greater in smaller and more connected habitat fragments, a consequence of
307 community domination by generalist species with high dispersal capacity (Marini et al., 2014). In
308 arable-dominated landscapes with high edge densities, 70% of pollinator and 44% of natural enemy
309 species attained their greatest abundance, pollination and biocontrol improved 1.7- and 1.4-fold, and
310 achieved greater yields (Martin et al., 2019). Others have similarly shown how smaller field size and
311 increased field border densities can elevate species abundances and pollination and pest regulation
312 services (Dainese et al., 2017; Garratt et al., 2017; Hass et al., 2018). Furthermore, heterogeneous
313 arable landscapes that contain large amounts of high quality field margin habitats providing floral
314 resources can lead to increased levels of reproduction and population size of bumble bees (Carvell et
315 al., 2017). In contrast, another large study found little evidence of landscape configuration influencing

316 bee species richness and abundance, apart from a negative relationship to social bee abundance
317 (Kennedy et al., 2013). Nonetheless, enhancing edge density in agricultural landscapes has the
318 potential to promote functional biodiversity and ecosystem services that enhance yields (**Fig. 3**). The
319 effects, however, will depend on the interaction of landscape structure with the response traits of the
320 service-providing organisms. For example, Martin et al. 2019 found that ground-dispersing generalist
321 natural enemies and pollinators whose larvae feed on crops or pests, were most abundant in arable-
322 dominated landscapes with few edges, presumably because they are well adapted to exploit
323 agricultural resources. Other pollinators and natural enemies that can fly benefit from high edge
324 densities and interfaces with semi-natural habitats at landscape scales and so a high density of
325 ecotones may be required for effective spillover of pollination or biocontrol services to the cropped
326 area (Martin et al., 2019).

327 The management of agricultural fields is an important driver determining the availability and
328 capacity of functionally important taxa to deliver ecosystem services. Soil organisms with their low
329 capacity for active dispersal are primarily influenced and operate at more localized spatial scales
330 (Veen et al., 2019), although patterns in land-use and non-cropped areas can sort and structure soil
331 communities over time at the landscape scale (Eggleton et al., 2005; Vanbergen et al., 2007). Below-
332 ground biodiversity is therefore mostly driven by field scale management practices such as tillage
333 practices and agrichemical applications, so longer-term management to mitigate the negative effects
334 of these practices can deliver benefits to below-ground biodiversity (Bender et al., 2016; Lal, 2006;
335 McDaniel et al., 2014). More mobile pollinators and natural enemies and the services they provide
336 are also consistently affected by in-field management, often in combination with the effects of
337 landscape context (above & Petit et al. this volume). Agricultural practices such as effects of fertiliser
338 application, independent of pollinator availability in the area, have been shown to affect the extent
339 that functionally important taxa contribute to crop output (Garratt et al., 2018a; Tamburini et al.,
340 2019). Rusch et al. 2016 showed how combined management of semi-natural habitat and crop rotation
341 can stabilize and enhance natural pest control in agricultural landscapes. Natural pest control of aphids

342 in cereal crops was maximized in complex landscapes with monotonous and short crop rotations and
343 minimized in simple landscapes with more diverse crop rotations that include perennial crops (Rusch
344 et al., 2013; Rusch et al., 2016). In a large scale study in European arable systems, enhancing natural
345 enemies and pest control by increasing landscape complexity proved to be disappointing in
346 intensively cropped fields with denuded soil conditions (Gagic et al., 2017). Moreover, despite the
347 evidence that organic agriculture [4.2.2] can elevate pollinator and natural enemy abundance and
348 diversity (Garratt et al., 2011; Katayama et al., 2019; Krauss et al., 2011), such benefits are not
349 ubiquitous and often depend on landscape context, the spatial scale of assessment and the organisms
350 concerned (Brittain et al., 2010; Schneider et al., 2014; Tuck et al., 2014)(Petit et al this volume).

351 In summary, agriculture has effects that operate from field to landscape scales, which impact
352 and modulate biodiversity and functionally important taxa delivering ecosystem services in support
353 of crop yields and ultimately human wellbeing (**Fig. 3**). Agriculture is therefore a major cause of
354 biodiversity loss and ecosystem degradation, but it also presents potential solutions to these
355 challenges to aid the transition towards sustainable development (**Fig. 4**).

356 **4. Alternative management approaches to conventional intensive agriculture**

357 The impacts of agriculture as a historical and current global driver directly shaping the climate,
358 biodiversity, landscapes and ecosystem functioning are well understood (IPBES, 2019; IPCC, 2019).
359 Although long acknowledged, the need to move towards more sustainable forms of agriculture has
360 become critical with the ongoing ecosystem change and degradation as the 21st century progresses.
361 One solution involves transformative changes in society at all levels of governance, policy and
362 practice to mitigate and reverse the adverse environmental impacts of human activities, including the
363 current paradigm of conventional agricultural intensification, while maximising environmental
364 resilience and food security (IPBES, 2019; Rockstrom et al., 2017). The precise forms that this future
365 agriculture should take remains, however, hotly debated.

366 Currently, there are several alternative agricultural systems to conventional intensification
367 (**Fig. 4, Table 1**). These vary in the role that technologies, management, external inputs or natural
368 processes are used to support future agricultural production as well as in the socio-economic context
369 determining the development and functioning of the farming system (Therond et al., 2017). Transition
370 to each of these different modes of sustainable agriculture requires differing levels of adaptation of
371 the farming management system. This ranges from optimising production and decreasing waste [4.1],
372 substituting external products or procedures with deleterious environmental effects with less harmful
373 procedures or with natural ecosystem processes [4.2], to a co-production of a new farming system
374 based on knowledge about the ultimate causes of inefficiencies and impacts to maximise agricultural
375 and environmental benefits [4.3] (Hill and MacRae, 1996; Pretty, 2018; Wezel et al., 2014). While
376 efficiency and substitution tend to be additive and incremental within current production systems,
377 redesign aims to transform the farming system but presents greater agricultural, social and
378 institutional challenges (Garibaldi et al., 2017; IPBES, 2019; Pretty, 2018; Therond et al., 2017) (see
379 **Skrimizea et al. this volume**). Thus, there are multiple alternative models of agricultural production
380 varying in their reliance on nature or technology and the degree to which land is ‘shared or spared’
381 (**Grass et al this volume**). These fall along a continuum ranging from relatively minor adjustments of
382 efficiency to a wholesale transformation of the farm management system, but it is important to
383 highlight the considerable overlap between them as they are not mutually exclusive and there is
384 potential for interoperability (**Fig. 4, Table 1**).

385 *[insert Figure 4, Table 1]*

386 **4.1 Optimisation of production through increased efficiency**

387 4.1.1 Sustainable Intensification of Agriculture

388 Sustainable intensification of agriculture (see glossary) remains conceptually close to the standard
389 model of conventional intensive farm management by relying on agri-technological solutions that
390 enable the inputs of agrichemicals to be optimised through greater precision of timing and targeting
391 (**Fig. 4, Table 1**). Sustainable intensification was originally conceived as an approach to increasing

392 crop yield whilst improving ecological and social conditions (Godfray et al., 2010; Pretty, 1997). It
393 posited reliance on agroforestry, conservation agriculture and biocontrol to establish low-input and
394 resource-conserving systems that promoted favourable ecological interactions within the
395 agroecosystem, rather than dependence on external inputs. This was found to improve yields and
396 livelihoods in developing economies (Godfray et al., 2010; Pretty et al., 2006). However, the more
397 recent conceptualisation of sustainable agricultural intensification has shifted the focus toward capital
398 and external input intensive solutions by both public and private parties (Tittonell, 2014) in order to
399 enhance resource use efficiencies (**Fig. 4**), such as irrigation or fertilizer applications via precision
400 agriculture (**Fig. 2e**) or use of genetic modification technologies (**Fig. 2c**) [5.2]. Smart systems that
401 integrate remote-sensing, geo-positioning, big data, machine learning, drones and robotics (**Fig. 2e**)
402 to precisely monitor crop and livestock health and target interventions (e.g. pesticide applications)
403 either already exist or are advanced development (Liakos et al., 2018; Partel et al., 2019; Pretty, 2018;
404 Wolfert et al., 2017). Coupled machine learning and ecological network modelling may offer a way
405 for the aligning ecosystem service management with smart crop management systems (Tixier et al.,
406 2013). There is great potential in these technological solutions to assure yield and reduce
407 environmental harms, but continued reliance on high-technology underpinned by access to finance or
408 data means that this approach may be limited to only a subset of farmers [5.2].

409 This has led to criticism that this concept does not promote social equity (Garnett et al., 2013;
410 Loos et al., 2014) and fails to go far enough by working within and with natural ecosystem limits and
411 processes (Rockstrom et al., 2017). As currently framed, sustainable intensification seeks to reduce
412 waste and environmental harm (e.g. by fine-tuning agrichemical delivery) and possibly include a level
413 of input substitution or crop diversification, but without radically adapting the conventional mode of
414 intensive agriculture towards a wholesale redesign of the production system (Lemaire et al., 2014;
415 Lin, 2011; Pretty, 2018; Wolfert et al., 2017). Therefore, where sustainable intensification of
416 agriculture (as currently framed) is practiced, future landscapes will likely be improved, but not

417 radically transformed in terms of conservation, management and use of beneficial biodiversity and
418 ecosystem services (**Fig. 4, Table 1**).

419 **4.2 Substitution of external inputs or environmentally harmful procedures**

420 4.2.1 Integrated Pest Management

421 Integrated pest management (IPM) is an approach that depends greatly on knowledge of pest biology
422 and ecology to allow tactical decision making by farmers in order to optimize the control of pest
423 organisms (pathogens, weeds, insects, vertebrates) in an ecologically and economically sound manner
424 (Ehler, 2006; Kogan, 1998). In its most basic form, IPM (see glossary) aims to reduce use of
425 environmentally harmful pesticides by choosing less toxic products or substituting chemical control
426 with natural biocontrol, with pesticides employed only once an economic threshold of pest damage
427 has been passed (**Fig. 4, Table 1**) (Ehler, 2006; Kogan, 1998). A broader interpretation, necessary for
428 delivering long-term pest regulation, sees IPM being employed as part of a re-design [4.3] of the crop
429 management system aimed proximately at lowering pest pressure, while reducing pesticide use and
430 ultimately providing economic savings for the farmer and protecting both the environment and human
431 health (Barzman et al., 2015; Colbach and Cordeau, 2018; Pretty, 2018). To reduce pesticide reliance
432 and maintain crop productivity, IPM seeks to optimize the synergy between a diverse set of pest
433 management tools (biological, chemical, cultural, and mechanical) coherently combined at the scale
434 of the cropping system, its rotations and the technical operations associated with each crop (Barzman
435 et al., 2015; Swanton and Stephan, 1991). IPM systems require profound knowledge of pest biology
436 along with interactive effects among pest management tools so as to promote longer-term synergies
437 that disrupt pest species' niches and prevent outbreaks of highly adapted pests (e.g., pesticide
438 resistance/tolerance) (Barzman et al., 2015). A sustainable IPM strategy should therefore combine all
439 available methods, including the judicious and targeted use of pesticides, to facilitate a reduction in
440 pest pressure. There are, however, challenges facing the implementation of IPM. In comparison to
441 use of chemical pesticides, IPM can be time consuming and complicated because of the need to

442 implement multiple, concurrent practices against all classes of pests (**Table 1**). Moreover it requires
443 the monitoring of pest populations to assure the implementation of the IPM tactic at the right time
444 and place. Agricultural consultants, with the requisite knowledge to provide farmers with independent
445 advice on the best tactics to employ within an IPM framework are not readily available in all parts of
446 the world (Ehler, 2006; Kleijn et al., 2019). Therefore, the effective use of IPM in support of
447 sustainable agriculture will require considerable reform of agricultural systems [4.3], knowledge
448 exchange, and socio-cultural change [5.6].

449 4.2.2 Organic agriculture

450 Organic farming (see glossary) emerged from the need for a holistic system for enhancing soil
451 fertility, water storage, and the biological control of crop pests and diseases (FAO, 2016; Reganold
452 and Wachter, 2016). This was traditionally associated with low-input, small-scale, diversified farms.
453 More recently the certification of organic farming has prohibited the use of most synthetic inputs and
454 GMOs while allowing organic fertilizers and pesticides (Gomiero et al., 2011; Reganold and Wachter,
455 2016). Consequently, many organic farms today practice input substitution (**Fig. 4, Table 1**) and
456 resemble conventional farms in that they are often high input, large-scale, and sustain low crop and
457 non-crop diversity, but differ in using permitted organic products instead of synthetic fertilizers and
458 pesticides (Guthman, 2014; Kremen et al., 2012). Similarly, there are low-input conventional farms
459 operating that may use some of the practices of organic agriculture but that are not certified as being
460 managed ‘organically.’ Currently, organic agriculture includes a wide spectrum of farming styles (**Fig.**
461 **4**) from smallholders to intensively managed large-scale systems (Gallé et al., 2019).

462 Organic agriculture has the potential to mitigate adverse effects of intensive farming. Species
463 richness, functional diversity and abundance of a wide-range of taxa are often higher on organic than
464 conventional farms (but see Brittain et al., 2010; Gallé et al., 2019; Gomiero et al., 2011; Hole et al.,
465 2005; Holzschuh et al., 2008; Katayama et al., 2019; Krauss et al., 2011; Schneider et al., 2014;
466 Wintermantel et al., 2019). Positive effects of organic agriculture on biodiversity vary among
467 landscape and crop types, levels of crop diversification. They are also contingent on the spatial scale

468 at which the impact is assessed and the identity of the organism and its capacity to tolerate, adapt or
469 respond to the management (Brittain et al., 2010; Gallé et al., 2019; Kremen et al., 2012; Schneider
470 et al., 2014; Tuck et al., 2014). There is often a difference in crop productivity per unit area between
471 conventional intensive agriculture and organic farming, with the former typically being higher
472 yielding (de Ponti et al., 2012; Gomiero et al., 2011; Reganold and Wachter, 2016; Schrama et al.,
473 2018; Seufert et al., 2012). Maintaining yield under an organic system may thus lead to expansion of
474 the cultivated land area, potentially risking further habitat loss (Seufert et al., 2012) [1.0; 3.0]. This
475 productivity gap can be narrowed by farm management, such as adoption of a diverse farming system
476 following the principles of ecological intensification [4.3] to improve crop interactions and
477 agroecological functions (Kremen and Miles, 2012; Ponisio et al., 2015; Seufert et al., 2012).
478 Although conversion to organic farming can lead to an initial yield drop, there is evidence that it
479 ultimately improves yield stability, albeit with some time lags (several years) and variation among
480 crop types (Andersson et al., 2012; Bedoussac et al., 2015; Ponisio et al., 2015; Schrama et al., 2018;
481 Seufert et al., 2012). Organic farming can bring financial premiums to the grower and improve
482 environmental outcomes (Gomiero et al., 2011; Reganold and Wachter, 2016). To achieve a level of
483 sustainable farm production over time requires organic farming approaches to move from input
484 substitution toward a redesign of the farm system, including modified management (e.g., sowing
485 rates, alternative crop varieties, mechanical weeding), crop diversification and use of nature-based
486 solutions [4.3] that assure beneficial biodiversity and ecosystem services (see glossary) (**Fig. 4**).

487 **4.3 Farming system redesign and nature-based approaches**

488 4.3.1. Ecological intensification

489 Ecological intensification describes an overarching set of principles and approaches to take a more
490 transformative and nature-based approach to agriculture (see glossary), which distinguish it from the
491 methods underpinning conventional or sustainable intensification. It aims to maintain or increase
492 long-term agricultural productivity, while reducing reliance on synthetic inputs and the need for

493 further land-use conversion, through effective management of nature's contribution to people (see
494 glossary) (Garibaldi et al., 2019). In common with sustainable intensification of agriculture, resource
495 use efficiency is sought by more precise and reduced (potentially 'zero') use of synthetic inputs.
496 However, the pre-eminent principle of ecological intensification is to confer greater resilience on the
497 farm system by working with co-existing biota and ecological processes to optimise soil fertility,
498 plant performance, crop pollination and natural defences against pests and diseases (**Fig. 4, Table 1,**
499 **Box 1**) (Bender et al., 2016; Bommarco et al., 2013; Kovács-Hostyánszki et al., 2017). This breadth
500 of nature-based objectives distinguishes ecological intensification from both IPM [4.2.1] and organic
501 farming [4.2.2] as typically practiced to date. Accordingly, ecological intensification is knowledge-
502 intensive requiring the active management of farmland (**Box 2**) to increase the intensity of the
503 ecological processes through ecological replacement or enhancement to close yield gaps (Bommarco
504 et al., 2013; Kleijn et al., 2019; TITTONELL, 2014) and is applicable to both large-scale and small-scale
505 [5.3] farming systems (Garibaldi et al., 2016).

506 [*insert Box 1*]

507 Despite technological improvements, the benefits of conventional agricultural intensification
508 are limited by the availability of ecosystem services or trade-offs occurring as a result of landscape
509 composition (Catarino et al., 2019; Deguines et al., 2014; Montoya et al., 2019). Assurance of crop
510 yield can only be achieved in the longer term by a sustainable management of biodiversity and
511 ecosystem services that accounts for landscape structure (**Fig. 4**). Practices commensurate with
512 ecological intensification and assurance of ecosystem services include the (re)establishment of
513 ecological infrastructures (e.g., hedgerows, floral or grass strips), preserving or creating natural or
514 semi-natural habitats within and adjacent to farms and modifying management to include
515 intercropping, reduced or no-till operations, or leaving a proportion of land fallow (Kovács-
516 Hostyánszki et al., 2017; Potts et al., 2016). Such an ensemble of approaches can benefit plant
517 microbiomes, soil decomposers, pollinators and natural enemies of pests that directly or indirectly
518 support crop production (Bender et al., 2016; Bommarco et al., 2013; Kleijn et al., 2019; Kovács-

519 Hostyánszki et al., 2017) (**Box 1**). Many of the practices under the umbrella of ecological
520 intensification will contribute to mitigating the drivers of decline in pollinators and other biodiversity
521 (IPBES, 2019; Kovács-Hostyánszki et al., 2017; Potts et al., 2016). Moreover, whilst currently
522 evidence is currently limited, there are examples of enhanced crop pollination and yield assurance
523 consistent with the application of ecological intensification (Blaauw and Isaacs, 2014; Feltham et al.,
524 2015; Pywell et al., 2015). Knowledge gaps remain, however. The extent that ecological
525 intensification can assure farm yields and profitability or those practices that are most effective for
526 achieving the outcomes and when and where they should be employed, is not well understood.

527 Ecological intensification can also make other contributions to people, but these require
528 participatory action, knowledge and training. Examples include improved human health from reduced
529 pesticide use, increased production of nutritious food in areas with greater agricultural diversity
530 (Herrero et al., 2017), and conservation of cultural heritages or traditions, such as the symbolic
531 meaning and use of different species and the diverse landscapes preferred by people in which to live
532 (Hill et al., 2019; Potts et al., 2016). As people hold different preferences or values, incorporating a
533 variety of nature's contribution to people is necessary to produce an environment contributing to high
534 value for all. Therefore, policies for land use should account for a plurality of views (legitimacy) and
535 be relevant to the needs of people with different socio-economic characteristics (salience). In many
536 respects, therefore, ecological intensification describes an ongoing process, an evolution rather than
537 an endpoint and should be considered a necessary pathway to meeting the objectives of sustainable
538 management, food security and resilience, and the broader goal of societal transformation (Garibaldi
539 et al., 2017; IPBES, 2019; Rockstrom et al., 2017). Below we consider two specific farming
540 approaches, conservation agriculture and agroecological farming, that we consider sit under the
541 auspices of ecological intensification, but which vary in their breadth of nature based solutions (see
542 glossary) and level of farm redesign.

543 4.3.1.1 Conservation Agriculture

544 As a farming system, conservation agriculture (see glossary) has a comparatively narrow focus on
545 the management of soil and water resources in support of crop production, placing it at the frontier
546 between substitution and nature-based approaches (**Fig. 4, Table 1**). Conservation agriculture
547 requires substantial modifications to the type, timing, and rotations of crops with an emphasis on
548 maintaining soil structure, beneficial soil biodiversity, water holding capacity and nutrient levels. It
549 seeks to achieve this by minimising physical soil disturbance (i.e., zero tillage approaches) and
550 agrichemical inputs, achieving a permanent soil cover using crop residues or living mulches to
551 increase soil carbon and fertility, and employing diversification of plant species through crop
552 rotations, use of cover crops, or intercropping (Giller et al., 2015). Through such actions, conservation
553 agriculture aims to achieve enhanced beneficial biodiversity and natural ecological processes, above
554 and below-ground, which contribute to increased water and nutrient use efficiencies and to improved
555 and sustained crop production (Garratt et al., 2018b; Oldfield et al., 2019). However, it does not
556 typically address other facets of agricultural management pertinent to ecological intensification such
557 as natural biocontrol and crop pollination services.

558 4.3.1.2. Agroecological farming

559 A specific application of the concepts and principles of ecological intensification to the [re]design of
560 the farm management system is agroecological farming (Wezel et al., 2014) (see glossary). This aims
561 to integrate environmental, sustainability and production goals by regenerating long-term
562 agroecosystem properties through the incorporation of functional biodiversity (Tscharntke et al.,
563 2012) (**Box 1**) alongside some technological or management innovations (**Box 2**) to produce a
564 sustainable, resilient system (Altieri, 1999; Altieri et al., 2015; Wezel et al., 2014). Agroecological
565 methods are knowledge, management, and labour intensive rather than external input intensive, and
566 are often rooted in traditional farming practices or are co-developed by farmers and scientists with
567 the aim to enhance food sovereignty (Altieri, 2004). A central tenet of agroecological farming is a
568 move away from monocultures that dominate the conventional approach to agricultural

569 intensification and towards the restoration or creation of a more complex and diversified agricultural
570 system (**Fig. 4, Box 2**). For instance, it can be achieved through the employment of farming practices
571 such as intercropping, permaculture, diverse crop rotations, conservation agriculture methods,
572 agroforestry and integrated crop-livestock management (Brooker et al., 2015; Herrero et al., 2010;
573 Iverson et al., 2014; Lemaire et al., 2014; Lin, 2011; Torralba et al., 2016). Integrating a diversity of
574 crops and/or animals in the production system promotes agro-biodiversity across scales, regenerating
575 or enhancing ecosystem services, and reducing the need for external inputs (Herrero et al., 2010;
576 Kremen et al., 2012; Kremen and Miles, 2012; Malezieux et al., 2009; Rudel et al., 2016) (**Table 1**).
577 Evidence suggests that diversified farming systems that integrate diversity of crops with livestock,
578 agroforestry and ecological infrastructure can improve natural biological control (Iverson et al., 2014;
579 Malezieux et al., 2009; Redlich et al., 2018) (**Box 1**) and pollination services (Hill et al., 2019; Potts
580 et al., 2016), thereby contributing to yield production and stability.

581 To be attractive to farmers, agroecological farming (and other alternative approaches) need to be a
582 viable economic option, either by demonstrating productivity broadly commensurate to that gained
583 through conventional methods or by providing greater economic or environmental resilience or by
584 attracting subsidies or finance for environmental outcomes (e.g. payment for ecosystem services or
585 environmental goods). More research is needed to provide evidence on the level of yield and
586 profitability that different ecological intensification approaches (agroecological farming conservation
587 agriculture) can attain relative to conventional intensification, particularly in different cropping or
588 environmental contexts. Crucially these effect sizes, their context-dependency and the knowledge-
589 intensive methods require close knowledge exchange and collaboration between scientists,
590 agronomic advisors and farmers to ensure that new practices are applied in appropriate ways (where,
591 when, how) that optimise production and environmental goals. This knowledge exchange, targeting
592 and uptake represents a major hurdle for the transition from conventional intensive agriculture to new
593 model agricultural systems. In many nations, there is a lack of independent agricultural advisors who

594 can interpret the science and provide advice on the best application of novel practices for a specific
595 context.

596 [*insert Box 2*]

597 4.3.2 Climate smart agriculture

598 Agriculture is the major factor contributing to climate change through habitat conversion,
599 conventional management practices, livestock emissions, and use of energy by industrial machinery,
600 transport and production of agrichemicals (IPBES, 2019; IPCC, 2019). Earth-system feedbacks mean
601 that future agricultural production and food security will be jeopardised by climate change and its
602 effects on the frequency and severity of extreme weather events and biodiversity loss (IPBES, 2019;
603 IPCC, 2019; Lobell et al., 2011; Potts et al., 2016; Steffen et al., 2018). Future agricultural expansion
604 and conventional intensification will only further increase greenhouse gas (GHG) emissions
605 exacerbating climate change and eliminating or degrading natural biodiversity and ecosystem
606 functions that confer Earth-system resilience (IPBES, 2019; Steffen et al., 2018). Increased climate
607 variability is therefore a global threat to ecosystem function, agricultural productivity, livelihoods of
608 farmers and rural communities and national economies, although the extent of these impacts is
609 projected to vary considerably among world regions and economies [5.1] (Garnett et al., 2013;
610 IPBES, 2019; IPCC, 2019). Addressing the impact of climate change in concert with the effects of
611 other direct and indirect drivers of global change is extremely complex and requires accounting for
612 socioeconomic conditions and environmental and temporal variations at all scales (IPBES, 2019;
613 Vermeulen et al., 2013).

614 Climate-smart agriculture (CSA) aims to moderate the impact of climate change on food
615 production (see glossary). CSA integrates economic, social and environmental aspects of sustainable
616 development in a framework to achieve both food security and a mitigation and adaptation to climate
617 change effects. It provides technical, political and investment solutions supported on three pillars: 1)
618 sustainably increasing agricultural productivity and incomes; 2) adapting and building resilience to
619 climate change; and 3) reducing and/or removing GHG emissions. The CSA approach is particularly

620 focussed on developing economies (e.g., in sub-Saharan Africa and south Asia) striving to meet the
621 interlinked challenges to food and nutritional security from yield gaps and increasing per capita
622 consumption rates, environmental degradation, and extreme climatic events [5.1] (IPBES, 2019;
623 Wheeler and von Braun, 2013; Zougmore et al., 2018).

624 The CSA approach promotes the joint use of existing agricultural systems and practices known
625 to benefit productivity alongside maximising nature's contributions to securing yields [4.2, 4.3] to
626 realise synergistic benefits for climate change adaptation and mitigation (**Fig. 4, Table 1**). Current
627 and future options (**Fig. 4**) deployable as part of re-designing management for a climate smart
628 agriculture include the use of integrated crop and agroforestry systems [4.3.1.2], IPM [4.2.1],
629 conservation agriculture [4.3.1.1], and new highly efficient crop or forage varieties that reduce GHG
630 emissions [5.3] or under-utilised, orphan crops [5.1] able to tolerate environmental extremes. For
631 example, in comparison to conventional management regimes, integrating beef production with
632 soybean rotations produced higher food production and lower GHG emissions per unit of human
633 digestible protein, as well as increased financial and production resilience to future climate change
634 (Gil et al., 2018). Climate-smart villages (CSV) or communities is a concept that works in conjunction
635 with the principles and practice of agroecological farming [4.3.1.2] to produce a socially-just system
636 that brings potential benefits and resilience to food production, environment and climate change
637 (Aggarwal et al., 2018; Altieri et al., 2015). Key to CSV is a multi-stakeholder, participatory approach
638 integrating natural, technological, management and institutional knowledge contributing to the
639 productivity and vulnerability of the system within a theory of change (Aggarwal et al., 2018). There
640 is great potential therefore for CSA to draw upon the suite of options available under the auspices of
641 sustainable and ecological intensification (**Fig. 4, Table 1**) to develop farm management systems that
642 deliver to the objectives of climate resilience, food security and environmental sustainability in ways
643 tailored to the specific context of different regions and peoples.

644 A major barrier to the implementation of CSA approaches are mismatches between existing
645 policies and climate-smart agricultural objectives including the implementation of technological

646 innovation (Long et al., 2016). Four key areas for improvement have been identified to facilitate the
647 implementation of CSA actions across all levels of decision making: (1) building evidence and
648 assessment tools and providing access for everyone to this information; (2) strengthening national
649 and local institutions including mainstreaming knowledge and practices across scales and sectors; (3)
650 developing aligned and evidence-based policies for climate change and agriculture; and, (4)
651 increasing financing and its effectiveness whilst reducing/eliminating perverse incentives (Aggarwal
652 et al., 2018; IPBES, 2019; IPCC, 2019).

653 **5. Key issues affecting the transition to more sustainable**

654 **agricultural landscapes**

655 Global crises such as climate change, biodiversity extinction, environmental degradation and
656 increasing inequalities have given rise to a growing criticism of the capacity of the prevailing
657 agricultural and food systems to support sustainable development from the local to the global level
658 and to a diverse call for sustainable transformations of these systems (Caron et al., 2018; IPBES,
659 2019; UN, 2015). However, the particular trajectory and possible form (**Fig. 2 b-e**) of future
660 sustainable agriculture(s) will be greatly affected by the outcome of social dynamics [5.1] and broad
661 societal trends e.g. urbanisation [5.1.1]; the relative potential for emerging technologies [5.2] and
662 nature-based solutions [4.3.1] to secure yields and minimise environmental harms; and the ecological
663 state of land and the economic scale at which the farming system operates [5.3].

664 **5.1 Social dimensions at the centre of agricultural transformations**

665 Implicit in the nascent agricultural reformation is the need for fundamental changes to the socio-
666 technical-ecological architecture of agricultural and food systems, including shifts in underlying
667 norms, values and power structures, and the introduction of new institutional structures (IPBES, 2019;
668 Patterson et al., 2017; Pelling et al., 2015). This refocus on social rather than (solely) agronomic or
669 technological change, along with the recognition of social justice and environmental integrity as the

670 normative goals of transformations in agricultural and food systems will be crucial issues affecting
671 future agricultural landscapes (**Fig. 2f**).

672 In this sense, the alternative farming approaches discussed above [4.0, **Fig.4, Table 1**] have
673 to be considered alongside the social and political dimensions they entail and the support they receive
674 from different societies or sections of society. Transformations to sustainable agricultural landscapes
675 will therefore depend on farmer's opportunities (access), challenges and choices [2.0], and will
676 involve trade-offs and possibly conflicts among societal actors e.g., urban dwellers, authorities or
677 other rural habitants (see below). Furthermore, the transformation of the agricultural system will not
678 only lead to modifications of the ecological landscape (**Fig. 2g**), but will also address issues of social
679 justice and equitability between producers, workers and consumers (Feola, 2015). For instance,
680 agroecology in Mexico is already expanding as a social and political movement led by indigenous
681 and peasant communities resisting the model of conventional (industrial) intensive agriculture and
682 aiming at food sovereignty (Toledo and Barrera-Bassols, 2017). There is therefore a need to address
683 the deeper roots of the sustainability issues such as the drivers of poverty, access to decision making,
684 social and economic context, vulnerability to climate change, etc. (Chandra et al., 2017). More
685 research is needed to understand the importance of individual motivations and market incentives
686 when facing changes and asymmetries in power dynamics at different scales (Dentoni et al., 2017).
687 Nevertheless, considering the social dimension of agricultural transformation (**Fig. 2f**) will be central
688 to avoid inducing unexpected or perverse outcomes in the structure, governance and sustainability of
689 future landscapes.

690 5.1.1 Urbanisation – a major societal trend affecting the future of agriculture and landscapes

691 An important global societal trend is the increasing urbanisation of people and landscapes, which
692 presents multifaceted risks and opportunities for sustainable agriculture and ecosystem health. This
693 will requires decisions to be made about which alternative mode of agriculture can be adopted, where
694 food production should be located with respect to population centres, and ultimately the values that
695 societies place on foods, biodiversity and ecosystem functions, goods and services (**Fig. 2**).

696 Urban agriculture is one option to address the multiple challenges of feeding people and
697 reducing environmental harms (**Fig. 2b**). Zero-acreage ‘Zfarming’ approaches advocate the
698 production of certain foods inside the urban or peri-urban zone, either on or inside built structures
699 under ambient or controlled conditions. By placing food production within the urban zone, Zfarming
700 has the potential to lower agriculture’s climate and environmental footprint, through closed circular
701 systems and reduced transport, while reconnecting urban people with food production and generating
702 other social benefits (Horst et al., 2017; IPBES, 2019; Orsini et al., 2013; Specht et al., 2014;
703 Thomaier et al., 2015; Zasada, 2011). However, Zfarming may be limited to certain types of crop or
704 farming approaches, encompassing a spectrum of management intensities ranging from extensively-
705 managed allotments or home gardens to highly-intensive production under controlled glasshouse
706 environments. It will therefore require careful planning and consideration of environmental and social
707 limits and outcomes, including accessibility and social justice (**Fig. 2f**) (Horst et al., 2017; IPBES,
708 2019; Orsini et al., 2013).

709 A current feature of urbanisation and its distancing of the human population from the process
710 of food production are growing shifts in the lifestyle, dietary expectations and choices of the
711 increasing urban population. In many world regions, cultures and societal groups, urbanisation has
712 been linked to greater economic affluence and a corresponding increase in consumption, including
713 demand for meat (IPBES, 2019; IPCC, 2019). There is, however, a growing societal debate over
714 modifying human diets and choices (meat consumption, flexitarianism, vegetarianism and veganism)
715 with much of the debate focussed on the potential benefits of reduced or zero meat-based diet for the
716 environment, animal rights and human health (IPBES, 2019; O’Keefe et al., 2016; Springmann et al.,
717 2018; Willett et al., 2019). Should this shift away from high meat-based diets, perhaps allied to the
718 development of alternative protein-rich foods [5.3] (**Fig. 2c**), continue and achieve widespread
719 cultural acceptability then it will elicit substantial changes in land-use and landscape structure (**Fig.**
720 **2g**) with projected benefits for climate change adaptation and mitigation (IPCC, 2019). The
721 consciousness of and demand for organic food, driven by rising public environmental awareness,

722 affluence and the perception that it is premium product (Reganold and Wachter, 2016), may represent
723 a model for marketing novel foods and those produced and branded using nature-based [4.3.1] or
724 climate-safe [4.3.2] farming solutions (**Fig. 2d, Fig. 4**).

725 Urbanisation is an engine of social and environmental changes. The global trend of migration
726 to cities from rural land in pursuit of work (Rigg et al., 2016) can lead to the partial or total
727 abandonment of farmed lands with complex consequences for people, biodiversity and ecosystems.
728 In extensively-managed landscapes of high biodiversity and cultural value this can lead to profound
729 changes in or losses of biodiversity post-abandonment due to the ecological succession or a transition
730 to other land uses (IPBES, 2019). Increased urbanisation and migration to cities in rapidly developing
731 economies are exacerbating the gender-asymmetry in smallholder agriculture [5.3] with women
732 taking an ever more important role as a knowledge holder and decision-maker with respect to farming,
733 income and expenditure as men often leave for urban work (Jost et al., 2016; Orsini et al., 2013;
734 Zimmerer et al., 2015). The intensity of rural depopulation has diminished in other places. Neo-rural
735 immigration from urban areas, motivated by economic considerations or the pursuit of another rhythm
736 of life in a historical and aesthetically attractive landscape has altered the social fabric of rural areas
737 (Hoggart and Paniagua, 2001).

738 The abandonment of farmland and change in social structure or attitudes, sometimes through
739 neo-rural immigration, can be seen as an opportunity for biodiversity conservation through land
740 sparing (**Grass et al. this volume**) for the restoration of biodiversity and good ecosystem functioning
741 (Henle et al., 2008; Navarro and Pereira, 2012; Queiroz et al., 2014). It may, however, also increase
742 the potential for conflict between societal groups with different values and worldviews (**Skrimizea et**
743 **al. this volume**). For instance, neo-rural immigrants or conservation groups may bring new priorities
744 for land-use focussed on nature protection and recreation that can conflict with the orientation and
745 expectations of local actors' like farmers. Hotly debated is the potential for ecological restoration (of
746 an ecosystem), reintroduction (of a species), and rewilding (of a managed area). These options, along
747 with afforestation for silviculture, biodiversity gains, or climate change mitigation, have been

748 identified as potentially beneficial processes and goals on abandoned or marginalised agricultural
749 land (Corlett, 2016; IPBES, 2019; IPCC, 2019). Restoration, reintroductions and rewilding aim to
750 meet international conservation objectives (e.g., Bern Convention and the Convention on Biological
751 Diversity, EC Directive on the Conservation of Natural Habitat and of Wild Fauna and Flora). The
752 objectives of local rural communities are sometimes overlooked, leading to potential conflicts
753 between societal groups (Coz and Young, 2020; Lorimer et al., 2015; Nogués-Bravo et al., 2016;
754 O'Rourke, 2014). Such conflicts have led to a recent emphasis on developing guidelines not only on
755 the ecological viability and risks of such initiatives (e.g., IUCN/SSC, 2013), but also on their social
756 feasibility and impacts (Butler et al., 2019). Such potential for social conflicts highlight the
757 importance of dialogue and consensus building to achieve understanding, coexistence and co-
758 development (**Fig. 2f**) of new configurations of agricultural landscapes (Mann and Jeanneaux, 2009;
759 Nohl, 2001; Redpath et al., 2015; von der Dunk et al., 2011).

760 Urbanisation is therefore an excellent example of a multifaceted social, economic, and
761 demographic phenomena impacting agricultural landscapes. The social changes and rising awareness
762 of environmental risks linked to urbanisation of the human population points to possible alignment
763 of sustainable agriculture, conservation of biodiversity and ecosystem services and climate adaptation
764 (**Fig. 2**).

765 **5.2 Emerging biotechnologies for crop breeding and novel foods**

766 Another component of the potential transformation of the food system with implications for the ways
767 in which landscapes are formed and utilised by humans are novel emerging technologies (**Fig. 2c**).
768 Conventional breeding and genetic modification of crop cultivars, a key pillar of the conventional
769 intensification of agriculture since the 'green revolution' of the 1960s, continue to offer opportunities
770 to enhance agricultural production through the production of improved varieties (Godfray et al.,
771 2010). Conventional breeding of plant lineages with back-cross selection of plant progeny with
772 desired traits over several generations continues, but the low genetic variability within cultivars after

773 millennia of domestication and the stochastic and time-consuming (typically 8-10 years) nature of
774 the process means it often fails to meet the demand for new varieties (Chen et al., 2019; Ghogare et
775 al., 2019). Transgenic modification involving the insertion of exogenous genes (e.g., bacterial
776 plasmids) coding for a desired trait into the genome of the target cultivar to create a new phenotype
777 expressing the trait (Chen et al., 2019) offers the potential to generate new crop varieties. For example,
778 future genetic improvements to reduce the dependence of certain crops on animal pollination of
779 fruit/seed set could offer the possibility of improving the quantity or quality of yields in light of
780 pollinator declines (IPBES, 2016). Although genetically modified crops circumvent the saturation of
781 genetic potential in highly-domesticated crop species and will continue to offer the prospect of
782 cultivar improvements, their release to market is limited by long and costly regulatory processes and
783 public concerns (Chen et al., 2019; Ghogare et al., 2019).

784 The most recent and now widely adopted approach to crop improvement is that of genome
785 editing (e.g., CRISPR/Cas9 and variants). This latest genetic manipulation tool allows the precise and
786 direct modification of a target endogenous gene(s) or regulatory processes or rearranging
787 chromosomes in a crop genome. This approach can precisely knock-out gene and regulatory elements
788 that confer negative, undesirable trait properties or restrict hybrid potential and knock-in, replace or
789 stack genes to elevate the expression of a desirable characteristic (Altpeter et al., 2016; Chen et al.,
790 2019; Ghogare et al., 2019). Such genome editing approaches have the potential to increase the
791 quantity and quality of yields, improve innate resistance to biotic and abiotic stressors, and increase
792 the production rate of desired hybrids (c.f. conventional and transgenic methods). Underpinned by
793 gene editing technologies, the emerging field of synthetic biology (Chen et al., 2019; Zhu et al., 2010)
794 may lead to crop improvements by re-engineering crop physiology through the insertion of artificial
795 DNA sequences to create novel cell and organism functions. One prospect is increasing
796 photosynthetic capacity by re-engineering enzyme pathways and chlorophyll antenna in
797 photosystems and optimising plant architectural traits to achieve gains in carbon metabolism and
798 lower photorespiration that lead to greater crop efficiency (Ort et al., 2015; Zhu et al., 2010). Another

799 alternative is the chemical manipulation of plant signalling using biosynthetic molecular precursors
800 to elicit physiological responses (e.g., resource allocation) that enhance crop yields and resilience to
801 environmental stress (Griffiths et al., 2016). As transformed cultivars move out of the lab and prove
802 themselves in field trials they may present further opportunities to enhance yields per unit area, avoid
803 further agricultural expansion and possibly allow for continued cultivation of land despite
804 environmental change and degradation.

805 Away from crop improvements, the pioneering technologies of synthetic biology, laboratory-
806 grown meat alternatives produced from vegetable, invertebrate or fungal protein, and food product
807 manufacturing with 3D bioprinting of proteins, may, individually or in combination, produce a viable
808 alternative to livestock farming (Mattick et al., 2012; Mouat et al., 2019; Portanguen et al., 2019;
809 Stephens, 2013). Should the drive towards synthetic or alternative ‘meat’ continue and become
810 acceptable to consumers, considered to be more ethical and marketable and scale-up for industrial
811 production (Mayhall, 2019; Portanguen et al., 2019) then, coupled with increasing urbanisation
812 [5.1.1], this raises the prospect of a high protein diet that can spare the land from raising livestock.
813 Where livestock grazing is intensive or requires habitat conversion, such a technological shift may
814 have potential benefits in reducing agricultural GHG emissions and providing an opportunity for the
815 restoration of biodiversity and ecosystems in the future landscape (IPBES, 2019; IPCC, 2019).

816 **5.3 The economic scale and ecological state of the farming system**

817 Another aspect that will influence the trajectory towards greater sustainability of the agricultural
818 system is the economic scale of the farming system and the ecological state of the landscape in which
819 it is situated. Conventional agricultural intensification characterised by industrial-scale food
820 production has spread worldwide and brought greater food security [1.0]. However, small-scale
821 agriculture (farm holding < 2 hectares, family-centred, **Fig. 5**) remains globally significant (FAO,
822 2015; Garibaldi et al., 2016; Lowder et al., 2019; Rigg et al., 2016; Steward et al., 2014; Zimmerer et
823 al., 2015) and includes culturally important crops and landscapes (Globally Important Agricultural
824 Heritage Systems (GIAHS) - Hill et al., 2019; IPBES, 2019). Small-scale agriculture is practiced

825 mostly in developing economies by an estimated 80% of the global rural population (~2.0-2.5 billion
826 people), representing 84% of the >600 million farms worldwide and producing an estimated 36% of
827 the world's food from only 12% of the global agricultural land surface (Lowder et al., 2019). Other
828 estimates suggest >70% of calories in Latin America, sub-Saharan Africa and parts of Asia are
829 produced by smallholder family farms (Samberg et al., 2016). Consequently, small-scale agriculture
830 is crucial to achieving food security (Lowder et al., 2019; Pretty et al., 2011; Rigg et al., 2016;
831 Samberg et al., 2016) and global policy targets for alleviating poverty, hunger and the transition to
832 sustainable agricultures (UN, 2015).

833 *[insert Fig. 5 here]*

834 Moving to a sustainable agriculture requires the balancing production of food alongside
835 environmental benefits [4.0] by optimising current approaches [4.1] with emerging technologies [5.2]
836 or substituting [4.2] or redesigning [4.3] farm practices through integration or reconstitution of
837 ecological infrastructure and nature-based solutions. The feasibility of the different options will be
838 dependent on the economic scale and resources along with the ecological starting point of the system.

839 Many of the options are compatible with large and small-scale agriculture, but these smaller
840 production systems also face a multiplicity of specific demographic, economic and environmental
841 challenges. They tend to be situated in economies in the lower brackets of household income, with
842 limited access to capital and technologies (Abdul-Salam and Phimister, 2017; FAO, 2015; Lowder et
843 al., 2019; Rigg et al., 2016). Food insecurity is likely to grow because the forecasted growth in the
844 global human population [2.0] will mainly occur in the low to middle income economies where small
845 holder agriculture predominates. This is especially the case in Africa where the predicted doubling of
846 the population by 2050 to 2 billion may produce a per capita decline in food production where 52.7%
847 of people already experience moderate to severe food insecurity (FAOSTAT, 2017; Pretty, 2018;
848 Pretty et al., 2011; Rigg et al., 2016; UN, 2019). Small-holder farmers in these developing economies
849 also face persistent yield gaps and economic vulnerability (Fermont et al., 2009; Lowder et al., 2019;
850 Tiftonell and Giller, 2013; Waddington et al., 2010). This is due to biophysical constraints, lack of

851 agronomic and agroecological advice, physical or financial infrastructure and economies of scale
852 (Abdul-Salam and Phimister, 2017; Pretty et al., 2011; Rusere et al., 2019a; Tittonell and Giller, 2013;
853 Zimmerer et al., 2015). Small-holder agricultural systems are also likely to be most affected by global
854 climate change, either directly because developing world regions will be most affected by earth
855 system impacts (e.g., increased drought, erratic precipitation) or indirectly because their economic
856 scale means they lack adaptive capacity (Chaplin-Kramer et al., 2019; Godfray et al., 2010; IPBES,
857 2019; IPCC, 2019).

858 Achieving a sustainable small-scale agriculture and nutritional security will require solutions
859 tailored to meeting these challenges and to their different socio-ecological history, land-use and
860 landscape structure (**Fig. 5**) (Hill et al., 2019; Rusere et al., 2019a; Rusere et al., 2019b; Tittonell and
861 Giller, 2013).

862 A feature of small-scale agriculture is that the people retain a closer, more direct link to food
863 production than most people in highly developed economies where large-scale agriculture prevails.
864 Smallholder farmers tend to be family-centred in terms of labour and reliance on the land for
865 household revenue (although this may also be the case in large-scale agriculture). Importantly, their
866 nutritional security, and that of the wider rural community, depend crucially on goods (crops,
867 livestock, non-food products) produced, sold and consumed at the household level (Lowder et al.,
868 2019) (**Fig. 5**). Improving financing opportunities, encouraging farmer-led cooperatives for
869 economies of scale and risk sharing, and promoting local-to-global value-chains that account for
870 social justice, equity and gender positions (Jost et al., 2016; Zimmerer et al., 2015) are vital to sustain
871 or improve yields and mitigate environmental and economic risks for small-scale, but also large-scale,
872 farm operations.

873 Efficiencies can be gained from leveraging access to improved crops, for both smallholder
874 and large-scale farmers, produced through genome editing technologies [5.2] (**Fig. 2c**) through
875 national research and industrial infrastructure, financial instruments and cooperative purchasing. This
876 includes the potential for the genetic improvement [5.2] and polyculture of orphan, underutilised crop

877 and agroforestry species (Dawson et al., 2019; Rosenstock et al., 2019) possessing traits that confer
878 greater economic and environmental resilience to farm yields. Most immediately, the use and
879 improvement of digital, mobile SMART technologies and basic electronic infrastructure (**Fig. 2e**) can
880 improve farm efficiencies and yields through better education, knowledge communication and mobile
881 applications to promote good practice, innovations and avoid malpractices (Abdul-Salam and
882 Phimister, 2017).

883 Unlike most industrial-scale systems, small-scale farmers already tend to employ diversified
884 approaches (**Fig. 4, Fig. 5**), including polyculture with minimal external inputs, combinations of cash
885 and subsistence cropping, and integration of livestock and agroforestry (Hill et al., 2019; Pretty et al.,
886 2011; Rosenstock et al., 2019). Consequently, landscapes dominated by small-scale agriculture tend
887 to be considerably more heterogeneous with respect to habitats and the organisms (**Fig. 3, Fig. 5**)
888 compared to large-scale systems transformed by conventional agricultural intensification [3.0] and so
889 may be on a potentially different trajectory.

890 Therefore, an opportunity exists to avoid environmental degradation by utilising the benefits
891 of an already diversified landscape and pool of service-providing organisms to deliver nature-based
892 solutions following the principles of ecological intensification (**Fig. 2d**) [4.3] (Garibaldi et al., 2016;
893 Garibaldi et al., 2017; Kovács-Hostyánszki et al., 2017; IPBES, 2019; Rockstrom et al., 2017; Rusere
894 et al., 2019a; Tittonell and Giller, 2013). Although there is some knowledge from temperate and
895 intensively managed large-scale systems on the links between landscape heterogeneity, biodiversity,
896 and ecosystem goods and services [3.0] (**Fig. 3**), there is comparatively less evidence on the
897 importance of beneficial agrobiodiversity in smallholder systems (Garibaldi et al., 2016; Steward et
898 al., 2014).. Therefore, further research is required to understand the applicability of transferring
899 evidence from more intensively-managed agricultural landscapes to small-scale systems, and vice
900 versa, and how diversified farming (livestock, traditional and cash crops, agroforestry) can be
901 integrated with nature-based approaches to increase the amount and stability of yields (Garibaldi et
902 al., 2017; Pretty, 2018; Pretty et al., 2011). Although also relevant to large-scale agricultural systems,

903 the potential design of agroecological [4.3.1.2] and diversified farming systems that contribute to the
904 building of a climate-smart agriculture [4.3.2] and resilient future food production is of particular
905 importance to low-income smallholder communities with the greatest vulnerability to global
906 environmental changes (Altieri et al., 2015; IPCC, 2019; Rosenstock et al., 2019).

907 **A**genda 2030 of the United Nations (UN, 2015) states: “...by 2030, double the agricultural
908 productivity and the incomes of small-scale food producers, particularly women, indigenous peoples,
909 family farmers, pastoralists and fishers, including through secure and equal access to land, other
910 productive resources and inputs, knowledge, financial services, markets and opportunities for value
911 addition and non-farm employment [SDG2: Target 2.3].” Integrating and targeting an ensemble of
912 technological (**Fig. 2c & 2e**) and nature-based (**Fig. 2d**) approaches for conserving biodiversity and
913 assuring farm productivity, drawing on the experience of small-scale and large-scale agricultural
914 systems, will help to promote sustainable agriculture, improve food and nutritional security and
915 minimise ecosystem risks [3.0].

916 **6. Conclusions**

917 Conventional intensive agriculture through field management and its effects on landscape
918 composition and structure is a major cause of biodiversity loss and ecosystem degradation, which
919 profoundly modifies functional biodiversity delivering ecosystem services to crop yields and human
920 wellbeing [3.0]. Agriculture also represents a interconnected and interlinked sector which can
921 influence the transition towards sustainable development and mitigating global environmental change
922 (**Fig. 2**). It is clear that the paradigm of conventional agricultural intensification requires reform to
923 dramatically reduce its worst effects and maximise the potential benefits of reconsidering the spatio-
924 temporal scale and diversity of farm management.

925 There exists a spectrum of alternative agricultural models, to an extent overlapping and
926 interoperable, varying in their reliance on nature or technology and the level of transformative change
927 required, ranging from adjustments to efficiency to a wholesale redesign of the farm management
928 system [4.0, **Fig. 4, Table 1**]. To reverse the ecological degradation of agricultural lands seen

929 worldwide and to shift it towards a sustainable system will require that nature-based approaches, like
930 those under the umbrella of ecological intensification [4.3], are placed at the core of future agricultural
931 management, but also the entire food system and value chains. This does not preclude a role for novel
932 technologies that help to optimise or facilitate increased production [5.3], but future technologies
933 must be applied alongside nature-based solutions in a systems approach and work within the limits
934 of the ecological landscape. Moreover, it is important to emphasise that no one solution is universally
935 applicable given the socio-economic and ecological heterogeneity worldwide, instead a future
936 agricultural system should comprise a suite of options (**Fig. 4, Table 1**) applied in the most efficient,
937 but environmentally sustainable and resilient way for each context (**Fig. 2**). We should draw upon the
938 best features of small-scale, diversified agricultural systems [5.1, **Fig. 5**], the positive effects of
939 extensive ecological infrastructure [3.0 & 4.3.1, **Fig. 3**] and the potential of new technologies [4.1.1,
940 5.3] to design future sustainable farm management systems that can be adjusted to the specific local
941 context (**Fig. 2**).

942 *[insert Box 3]*

943 This transformation of the agricultural system to meet the challenges of our time requires
944 active research (**Box 3**) and stakeholder co-development over the coming decade to realise future
945 sustainable farming approaches. While food production will remain key, diversification of farm
946 practices in terms of crop rotations, integration of livestock and/or trees, and the creation of ecological
947 infrastructure for ecosystem service delivery will combine to produce heterogeneous landscapes that
948 deliver biodiversity restoration and multiple contributions to human well-being (Díaz et al., 2018)
949 (**Fig. 2**). Social and demographic drivers such as those associated with urbanisation [5.2] will also
950 greatly influence the future landscape. Translocation of intensive food production to the urban zone,
951 shifts in cultural attitudes or diets due to an urbanising population, or technological advances (e.g.,
952 meat-free protein, synthetic biology, 3D bioprinting) may create opportunities for changes to
953 agricultural landscapes by switching to alternative land-uses delivering other environmental goods
954 (timber, bioenergy, fibre) or ecosystem benefits (carbon sequestration, biodiversity restoration).

955 Further complexity and potential constraints emerge from differing worldviews (and potential
956 conflicts – see Skrimizea et al. this volume) among societal groups about their relative roles and
957 responsibilities, rights and social and cultural norms. Considering the social dimension is thus crucial
958 to the success of agricultural transformation and the outcomes for food security and reversing the
959 adverse human impacts on the environment [5.6] (Fig. 2).

960 Shifting to an alternative agricultural paradigm, if done properly, will encompass
961 multifunctional landscape planning and cross-sectoral integrated and participatory management.
962 Therefore it will span multiple policy sectors, actors and knowledge holders requiring decision-
963 making processes to become interoperable in an effective way to avoid unanticipated or perverse
964 outcomes and inter-sectoral competition for finite land resources (IPBES, 2019) (Fig. 2). Science in
965 conjunction with indigenous and local knowledge (ILK), must have an important role in this
966 evidence-informed policy to guide decision making through the complexity and interconnectedness
967 of the natural world and the agricultural and food system. Trans- or inter-disciplinary approaches
968 integrating biological, social and economic sciences to understand better the merits of different modes
969 of agriculture in assuring yields, nutritional security and social justice will be essential. Alternative
970 modes of agricultural management can achieve high yields and profits (Reganold and Wachter, 2016),
971 but evidence of the simultaneous impacts of farming systems on ecological, social, and economic
972 aspects of sustainability are scarce (Garibaldi et al., 2017). The study of each aspect belongs to
973 different research fields, each with its own idiosyncrasies and vocabulary. An increase in the number
974 of studies that use a common framework to quantify these multi-faceted impacts would facilitate the
975 finding of high-level patterns to help understand what solutions are most likely to work in which
976 situations, across regional and national lines, and across specific farming systems.

977 The current food system is seen as the driver of many negative impacts on the global
978 environment by both key intergovernmental organisations (CBD, 2014; IPBES, 2019; IPCC, 2019)
979 and the scientific community (Kovács-Hostyánszki et al., 2017; Newbold et al., 2016; Potts et al.,
980 2016). Priorities need to be established for identifying farming systems that can generate benefits in

981 multiple dimensions, whilst eliminating negative externalities and accepting solutions tailored to
982 different environmental, political and social contexts (DeLonge et al., 2016; Kleijn et al., 2019)
983 (**Fig.2, Fig.4, Table 1**). The scientific literature sometimes complicates the debate by failing to
984 distinguish between the different objectives implied by concepts of agricultural production versus
985 food production versus food security (Garibaldi et al., 2017). Moreover there is a mismatch between
986 scientific understanding of alternative approaches such as ecological intensification and uptake by
987 farmers (DeLonge et al., 2016; Kleijn et al., 2019). Space should be given to other knowledge holders
988 and practitioners (e.g., farmers, agricultural extension services, business and industry, indigenous
989 peoples) to engage with scientists to ensure that new agricultural systems emerge from a dialogue
990 that helps to assure lessons are learned, conflicts avoided and multiple outcomes achieved. Moreover,
991 sustained and radical political commitment at the highest levels (Pe'er et al., 2020) is needed to build
992 upon intergovernmental agreements (CBD, 2014; IPBES, 2019; UN, 2015). New national and
993 international policies, levers and incentives (e.g., payments for environmental goods and services;
994 new certifications and labelling for quality control and consumer informed choices) (Pe'er et al., 2020)
995 are required to deliver the interlinked goals of food and nutritional security, environmental restoration,
996 poverty reduction and local development.

997 Agriculture relies on beneficial biodiversity and ecosystem processes, but it is also a socio-
998 cultural and industrial practice driving major ecosystem degradation and biodiversity extinction. This
999 means that agricultural reform is a necessity for a transition to sustainable food production,
1000 responding to global change and safeguarding food and nutritional security. There are a plethora of
1001 options to address the challenges of feeding a world with a growing population and per capita
1002 consumption pattern, in an equitable way, and assuring the restoration of biodiverse and resilient
1003 ecosystems. The ultimate key to the successful transformation of agriculture and the landscapes it
1004 supports are people and their capacity to accept new ways of living and working in response to the
1005 current environmental crisis.

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1007 7. References

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