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1 **REVIEW**

2 **OneARK: Strengthening the links between animal**  
3 **production science and animal ecology**

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26

## 27 **Summary**

28 1. Wild and farmed animals are key elements of natural and managed ecosystems that deliver  
29 functions such as pollination, pest control and nutrient cycling. They are submitted to global  
30 changes with a profound impact on natural range and viability of animal species, emergence and  
31 spatial distribution of pathogens, land use, ecosystem services and farming sustainability. We  
32 urgently need to improve our understanding of how animal populations can respond adaptively  
33 and therefore sustainably to these new selective pressures.

34 2. In this context, we explored the common points between animal production science and animal  
35 ecology to identify promising avenues of synergy between communities through the transfer of  
36 concepts and/or methodologies, focusing on seven concepts that link both disciplines. Animal  
37 adaptability, animal diversity, selection, animal management, animal monitoring, agroecology and  
38 viability risks were identified as key concepts that should serve the cross-fertilization of both  
39 fields to improve ecosystem resilience and farming sustainability.

40 3. The need for breaking down interdisciplinary barriers is illustrated by two representative  
41 examples: i) the circulation and reassortment of pathogens between wild and domestic animals  
42 and ii) the role of animals in elementary cycles

43 4. *Policy implications.* Our synthesis identifies the need for knowledge integration techniques  
44 supported by programs and policy tools that reverse the fragmentation of animal research  
45 towards a unification into a single Animal Research Kinship, OneARK, which sets new objectives  
46 for future science policy.

47 5. At the interface of animal ecology and animal production science, our article promotes an  
48 effective application of the agroecology concept to animals and the use of functional diversity to  
49 increase resilience in both wild and farmed systems. It also promotes the use of novel monitoring  
50 technologies to quantify animal welfare and factors affecting fitness. These measures are needed  
51 to evaluate viability risk, predict and potentially increase animal adaptability, and improve the

52 management of wild and farmed systems, thereby responding to an increasing demand of the  
53 Society for the development of a sustainable management of systems.

54

55 **Keywords** Adaptation, Agroecosystem, Bio-logging, Emergence, Functional diversity; Livestock,  
56 Phenotypic plasticity, Resilience, Sustainability, Zoonotic disease.

57

## 58 **Introduction**

59 Our planet is undergoing major global environmental changes mainly caused by a rapid increase  
60 in human population and the concomitant agriculture industrialisation (specialization,  
61 concentration, intensification). These changes have a profound impact on biodiversity, on land  
62 use due to modified resource availability, as well as on emergence and spatial distribution of  
63 pathogens (Keesing et al. 2010). A primary concern is the extremely rapid rate of these changes,  
64 which applies strong and often novel selective pressures on animals, at scales rarely encountered  
65 over evolutionary time scales. These challenges are placing new demands on physiological and  
66 adaptive capacities (particularly phenotypic plasticity which permits compensation of rapid  
67 environmental changes when genetic adaptation is too slow), on the interactions among species,  
68 and ultimately on species persistence and biodiversity. The consequences are major in terms of  
69 conservation of biodiversity but will also have impacts on every category of ecosystem services:  
70 support (e.g. soil formation), production (e.g. milk and meat), regulation (e.g. pest control) and  
71 cultural (e.g. ecotourism). Thus, we have a responsibility to find new ways to better understand  
72 and preserve the functional diversity of ecosystems. These have been, and will continue to be, a  
73 major support of human endeavours.

74 Animals represent an enormous part of biodiversity, contributing 1.12 million catalogued species  
75 from a total of 1.43 species throughout eukaryotic kingdoms (Mora et al., 2011). Only a very  
76 limited number of species are farmed but they contribute a significant amount of biomass. Wild  
77 and farmed animals are landscape shapers and ecosystem engineers that control the availability  
78 of resources to other organisms by causing changes in biotic or abiotic materials. However,  
79 animals are also important vectors, intermediate hosts and reservoirs for microorganisms causing  
80 major infectious diseases (Woolhouse et al., 2005). Additionally, wild and farmed animals have  
81 always been a major source of proteins for human consumption.

82 It is increasingly recognized that there is a continuum between animals in managed ecosystems  
83 and animals in natural environments. No production system whatever its level of biosecurity is  
84 completely isolated from the surrounding environment. Likewise, today, no ecosystem is

85 completely isolated from human influence, and increasingly ecosystems are subject to some  
86 degree of human management, or have limits imposed on them by human activity. Therefore, it is  
87 highly relevant to consider what the cross-fertilisation between the two communities of animal  
88 production science and animal ecology can bring.

89 A number of basic concepts appear at first sight to be fundamentally different between animal  
90 production science and ecology. However, when these concepts are given due consideration it  
91 transpires that they are actually more similar and not really in opposition. The aim of this paper  
92 is to explore the common points between animal production science and animal ecology. Better  
93 recognizing the similarities between the two communities will identify promising avenues of  
94 synergy by concept and/or methodology transfers between communities. This prospective  
95 thinking for a community unification into a single Animal Research Kinship, i.e. OneARK, sets new  
96 objectives for future science policy.

### 97 **Artificial selection versus natural selection**

98 Selection denotes the fact that, among individuals born at a given generation, those that will  
99 survive to mate and procreate a new generation can be considered as "chosen" according to some  
100 of their characteristics. These characteristics typically impact on their survival, mating probability  
101 and their number of descendants. For domestic species, **artificial selection** depends on decisions  
102 taken by humans (breeding managers). For wild species, **natural selection** emerges from  
103 interactions with conspecifics, other species and the abiotic environment.

104 Natural selection can act simultaneously on multiple traits, so that trade-offs are an important  
105 part of understanding adaptation and response to selection: natural selection maximises average  
106 fitness of the population, not trait values (Stearns, 1977). Another fundamental aspect is that  
107 natural selection varies spatially and temporally depending on the environment (Siepielski et al.,  
108 2013, 2017) so that traits may be positively selected in one environment and counterselected in  
109 another. Investigating selection is thus complex notably because we need to assess the actual  
110 target of selection but also make sure that the covariances between trait and fitness are not only  
111 due to environmental covariance (Morrissey et al., 2010).

112 It is generally admitted that artificial selection started in the early stages of domestication, the  
113 first selected traits being favourable to the domestication process itself, e.g. docility. During the  
114 last three centuries, and especially during the last six decades, this artificial selection was more  
115 and more organized and intense, targeting and maximising specific traits (e.g. dairy production,  
116 body mass). Another consequence of domestication was to decrease the natural selection  
117 pressure because humans increasingly controlled the environment of animals. This is typified by  
118 the strong intensification of animal production.

119 Whereas domestication first led to a huge increase in diversity between populations (Darwin,  
120 1859), the recent changes in livestock production led to the opposite, with a decrease in the  
121 number of breeds for a given species (Sherf, 2000) and a reduction of within-population genetic  
122 variability in intensively selected populations (Danchin-Burge et al., 2012). The selection of highly  
123 specialised and homogeneous individuals led to (i) decreased robustness and lower adaptive  
124 potential (e.g. lower resistance to environmental variability, particularly stress and disease) and  
125 (ii) the exacerbation of trade-offs such as milk production vs fertility (Oltenucu & Broom, 2010).  
126 The multivariate nature of selection acknowledged by animal ecologists (Lande & Arnold, 1983)  
127 has promoted the development of artificial selection programs which include the use of selection  
128 on multiple traits (Puillet et al., 2016).

129 Such collaborative efforts are increasingly needed because the rapid and strong changes of  
130 environmental conditions generate strong selective pressures, so much so that humans are now  
131 considered as the greatest evolutionary force (Palumbi, 2001). Understanding how populations  
132 respond to these new selective pressures is a key issue in applied evolution and conservation. It  
133 is also a key issue for artificial selection since global changes are altering the environmental  
134 conditions under which artificial selection is operating. A major challenge is to understand how  
135 global environmental changes are going to affect selective pressures acting on both wild and  
136 domesticated populations and whether populations are able to respond adaptively (and therefore,  
137 sustainably) to these new selective pressures.

138 **Agro-ecosystems and farmed animal management versus ecosystems and wild**  
139 **animal management**

140 In contrast to wild animals in natural ecosystems that are fully in interaction with the  
141 environment, the magnitude of interactions of farmed animals with the environment spreads  
142 along a continuum, ranging from agro-ecosystems to landless livestock production. This gradient  
143 is driven by the form of the feeding system, opposing land sharing to land sparing, and the level of  
144 interaction the livestock population has *vis-a-vis* agricultural and natural system components  
145 (crops, forest, water, wildlife, etc.). Agro-ecosystems are defined by a high dependence on local  
146 resources, like land and water (pastoralism being its apogee). At the opposite end of the scale,  
147 landless livestock systems maximize their direct independence from environmental constraints  
148 by means of feed trade, thus establishing production systems with almost no direct relation  
149 (excluding by the market) between the places and times where livestock are reared, their food is  
150 produced, and where their products are consumed.

151 Gradients in degree of human intervention are also a common element of wild animal and natural  
152 ecosystem management. Indeed, not a single natural ecosystem is human-proof, at least since  
153 climate change started. More direct wild animal ecosystem management profiles can range from  
154 biodiversity reserves through natural parks, run as wildlife sanctuaries, to wildlife areas managed  
155 by local communities, which recognize combined wildlife, livestock, and rangeland services as  
156 essential for human groups, a vision emphasized in Southern Africa (Chomba et al., 2014; Jones et  
157 al., 2015).

158 In the latter case there is a strong interaction between agricultural activity and ecosystem  
159 management. More generally, the frontier between the “wild” and the “farmed” animals is  
160 progressively being eroded, changing to situations where more coexistence and interactions are  
161 inevitable if we wish to reconcile preserving biodiversity and better resource sustainability.  
162 Achieving this in the design of these re-expanding agro-ecosystems imposes a tightening of the  
163 collaboration between animal production scientists and animal ecologists. An example of this is  
164 the “Natura 2000” policy to preserve biodiversity in Europe, often in human-made ecosystems.

165 Furthermore, and in line with societal considerations, there is a visible shift in livestock and  
166 wildlife policy dialogue, moving beyond the simple support of resource sufficiency and food  
167 provision to now provide incentives for conservation and rehabilitation of functional integrity,  
168 and payment for environment services in production areas and at global Earth scale (Frost et al.,  
169 2008; Kammlı et al., 2011).

## 170 **Viability risks for farmed systems versus natural ecosystems**

171 Global changes pose a viability risk for both natural and farmed systems, although the “currencies”  
172 by which viability is judged have traditionally differed; being largely about economics for farmed  
173 systems and about biodiversity and population persistence for natural ecosystems. The most  
174 commonly used currency to assess viability in wild populations is the probability of extinction of  
175 a population over an arbitrarily chosen time period (e.g. 100 years in the UICN red list) or the  
176 median time to extinction. Several components of global change will affect viability of both natural  
177 and farmed systems.

178 The impacts of **climate change** emerge through both long-term changes in average conditions  
179 within local environments and an increase in the frequency of extreme events (Ummenhofer &  
180 Meehl, 2017). The former has received more attention so far. The effects of climate change can be  
181 mediated through many indirect effects such as the disruption of interaction between species  
182 because of changes of phenology or morphology (van Gils et al., 2016). A typical example is the  
183 earlier breeding of insectivorous birds so that the peak of offspring energetic needs coincides with  
184 the peak of food abundance (caterpillars, Visser et al., 1998): if the timing is mismatched then  
185 breeding success is low. These effects are more likely to be encountered in wild than farmed  
186 system where long-term changes in average environmental conditions will more frequently be  
187 experienced in terms of direct effects that reduce resource availability. In farmed systems, these  
188 will typically impact the stocking densities of animals that are sustainable in extensive systems,  
189 and incur greater costs for intensive systems (e.g. cooling systems). In managed populations,  
190 extreme events such as drought or flooding require the farmer to make costly, unplanned  
191 interventions (buying food, transporting animals) where possible. These clearly have economic

192 consequences especially if possible interventions are limited and loss of animals occurs (e.g.  
193 rangeland grazing). In wild populations, effects of extreme events include both decreased survival  
194 (e.g. die-offs, McKechnie & Wolf, 2010) and reduced breeding success (Jenouvrier et al., 2015).  
195 Extreme events may generate very strong selection pressures leading to marked evolutionary  
196 shifts in wild populations (Grant et al., 2017). However the impact of extreme events is  
197 particularly complex to anticipate, as they engage non-linear shifts in multi-species interactions.

198 **Introduced exotic species**, which may be pathogens, pathogen carriers, predators or directly  
199 competing species, represent another major viability risk to both farmed and wild populations  
200 (Bellard et al., 2016; Paine et al., 2016; see section on circulation of zoonotic pathogens). They are  
201 particularly prevalent and successful in highly anthropized habitats such as peri-urban and  
202 agricultural lands, and species of tropical origin benefit from the warming climate in temperate  
203 and boreal regions.

204 **Land use** is another class of viability risks. There are direct economic impacts of human  
205 movement in terms of (i) the value of land or other shared resources such as water in zones where  
206 agricultural land is in competition with urban development, and (ii) in terms of rural depopulation  
207 (difficulties in recruiting labour, human isolation, costly supply chains) affecting ecological  
208 function of agro-landscapes (Sabatier et al., 2014). Extinction risks are further increased for wild  
209 populations due to competition with urban and agricultural land (e.g. palm oil, cocoa), and non-  
210 sustainable harvesting (Maxwell et al., 2016). To fully understand viability risks, all these factors  
211 and their interactions need to be taken into account.

212 There are also viability risks due to rigidity of **human behavior**. In farming this translates to, for  
213 example, continued use of inappropriate animal genetics through a failure to recognize the traits  
214 needed for durability in new conditions, or lack of flexibility in day-to-day farm management. The  
215 loss of genetic diversity of domesticated breeds due to rigid selection of a very few breeds is a  
216 major issue being addressed by the FAO (FAO, 2015). Rigidity of behaviour can also apply to  
217 animal species if we look at generalists/specialists or plastic/non-plastic species. One issue is the  
218 existence of ecological traps where species respond to cues that were supposed to signal high

219 quality environment but that got uncorrelated from this environment, for example asphalt roads  
220 may reflect light in the same manner as water bodies attracting some insects to breed (Schlaepfer  
221 et al., 2002). Ultimately, population viability will depend on the ability of organisms to respond  
222 adaptively to complex environmental changes inducing novel selective pressures.

223 Both farmed and wild populations share some of the same viability risks and ultimately must  
224 respond by adaptation (microevolution and/or plasticity). The degree of management of the  
225 animal populations within a given ecosystem will mainly affect the extent to which risks can be  
226 buffered by human intervention, e.g. deploying reproductive technologies developed in animal  
227 production science to aid in rewilding and to overcome habitat fragmentation. Biodiversity and  
228 economics are connected across the spectrum from farmed to natural ecosystems. Tools  
229 developed in ecology, such as coviability analyses (Mouysset et al., 2014), which aim at finding  
230 compromises where viability of both farmed and natural systems can simultaneously satisfy  
231 different constraints, will be important for the future.

### 232 **The key role of animal adaptability to connect evolutionary and animal** 233 **production sciences**

234 Adaptation processes are multifaceted, taking place at different scales with different temporal  
235 modalities (Gould & Lloyd, 1999). Evolutionary biologists, who mainly deal with natural  
236 populations, have focused on adaptation as a trait increasing relative fitness, *i.e.* which evolved via  
237 natural selection. Physiologists, who deal with laboratory and farmed strains, have focused on  
238 within lifetime reversible processes that allow individuals to adjust to their environment, with  
239 less focus on their heritability. These biological processes depend on the variability of the  
240 environment and adaptation can be described by the following continuum: (i) phenotypic  
241 flexibility of individuals leading to temporary/reversible changes, (ii) developmental plasticity  
242 leading to more permanent changes of phenotypes through physiological and/or epigenetic  
243 mechanisms, and (iii) intergenerational modification of allele frequencies through natural  
244 selection (Chevin & Beckerman, 2011). Integrating these different adaptive mechanisms has to be  
245 developed together with the interface with animal production science. Studying performance and

246 behavioral changes induced by modifications in the farming environment would provide a great  
247 opportunity for evolutionary biologists to investigate the key mechanisms allowing individuals to  
248 maintain their performances over different abiotic conditions, complementing and providing a  
249 bridge between approaches in the lab and in the wild.

250 The complex phenotypes underlying adaptability are forcing scientists to develop an integrated  
251 approach looking at multiple characters. The recent expansion of genomics, and other -omic data,  
252 offers new avenues to understand the mechanisms that shape adaptability (Valcu & Kempenaers,  
253 2014). Studying organisms as a whole, taking into account functional links between traits is now  
254 made possible by combining -omic data with the characterization of physiological and  
255 performance traits (Prunet et al., 2012). This should uncover cell or physiological processes  
256 important for adaptability in both wild and farmed animals. However, such approaches often  
257 produce big data on cell and physiological pathways concomitantly affected. Building an  
258 integrated phenotyping (Headon, 2013) that sorts out mechanisms underlying adaptability in an  
259 order of importance now needs to combine biological, bioinformatics and statistic knowledge.

260 Important questions remain regarding the role of transgenerational adaptation pathways in  
261 fitting, in the long term, populations to their environment. Such phenotypic modulation has a  
262 predictive power and may help the offspring to be better adapted to future environmental  
263 conditions. Intergenerational plasticity encompasses various mechanisms, including epigenetic  
264 changes. These mechanisms are likely to sustain rapid adaptation and to promote survival of the  
265 next generation (Rey et al., 2016). Their understanding is also a key element for animal production  
266 science: it opens an innovative way to optimize productivity, *via* the modulation of farming  
267 conditions during reproduction and offspring growth.

268 This is not an exhaustive list of the research of interest that remains to be conducted on animal  
269 adaptability. However, it emphasizes that promoting the understanding of the link between  
270 adaptation and fitness (survival or health state) and of the inheritance of related processes will  
271 enhance our ability to predict adaptability of animal populations, living in the wild or under  
272 farming conditions.

## 273 **The importance of animal diversity for system resilience**

274 Ecological resilience focuses on the adaptive capacity of an ecosystem and is defined as the  
275 amount of disturbance this system can absorb while remaining within the same stability range  
276 and retaining the same function(s), achieved through reinforcing within-system structures,  
277 processes and reciprocal feedbacks (Holling, 1996; Kaarlejärvi et al., 2015).

278 Resilience strongly depends on the initial composition of the local ecological assemblage and the  
279 degree of disturbance (Sasaki et al., 2015). In highly disturbed areas, differences in the recovery  
280 trajectory of assemblages have been related to differences in the composition and the dispersal  
281 capacities of the surrounding species pool of colonists and the level of connectivity among  
282 populations, species and ecosystems (Allison, 2004). These factors influence both probability of  
283 species persistence by increasing the genetic diversity of local populations (Bach & Dahllöf, 2012)  
284 and capacity for recovery by providing sources of propagating organisms (de Juan et al., 2013).

285 Biodiversity, a key factor for improving the long-term resilience of ecosystems (Awiti, 2011; Mori  
286 et al., 2013; Oliver et al., 2015), is frequently associated with high functional redundancy (*i.e.*  
287 presence of several species able to perform similar functions) (Sasaki et al., 2015; Kaiser-Bunbury  
288 et al., 2017) and high species complementarity (Lindegren et al., 2016). Both taxonomic (TD) and  
289 functional (FD) diversities, but not species richness, adequately capture the aspects of  
290 biodiversity most relevant to ecosystem stability and functionality (Mori et al., 2013). TD  
291 enhances resilience because most of the rare species within an assemblage are considered as  
292 functionally similar to the dominant ones and able to compensate their potential loss under  
293 changing environmental conditions, thus maintaining ecosystem functions. FD improves  
294 resilience because a more diverse set of traits increases the variety of potential responses to  
295 disturbance. This then increases the likelihood that species can compensate function(s) for one  
296 another lost during disturbance events (Moretti et al., 2006; Kühsel & Blüthgen, 2015). However,  
297 resilience is also likely to be scale-dependent (Shippers et al., 2015), *i.e.* a combination of traits  
298 providing resilience to small-scale disturbance can be ineffective against disturbance acting at  
299 largest scale. As a result, the link between biodiversity and resilience is sometimes weak

300 (Bellwood et al., 2003). If the trait structure of highly diverse animal assemblages remains rather  
301 stable after moderate stress, further intensification of human pressure can substantially reduce  
302 the variety of traits and results in significant alteration of functional diversity (Bregman et al.,  
303 2017). This raises the question of how to manage resilience and ecosystem services in socio-  
304 ecological systems?

305 Conceptual frameworks, tools and indicators (Sasaki et al., 2015; Oliver et al., 2015) have been  
306 defined for quantifying the resilience of coastal fisheries, estuaries or agricultural landscapes (de  
307 Juan et al., 2013; Mijatović et al., 2013) based on structural and functional attributes; *e.g.*  
308 ecosystem elasticity or sensitivity and adaptive capacity (López et al., 2013). Trends in the  
309 frequency of animal species that provide key ecosystem functions in Great Britain, have  
310 highlighted that key ecosystem functions are not equally impaired by global change, and  
311 conservation actions should focus on the functional groups for which there is clear evidence of  
312 resilience erosion (Oliver et al., 2015). Moreover, community field experiments have clearly  
313 shown that vegetation restoration can improve pollination, suggesting that the degradation of  
314 ecosystem functions is at least partially reversible (Kaiser-Bunbury et al., 2017) and that severe  
315 disturbance-driven reduction in ecosystem function does not preclude rapid ecosystem recovery.  
316 Several pattern- or process-oriented strategies have been suggested (Pauly et al., 2002; Fischer et  
317 al., 2006) to enhance biodiversity and ecosystem resilience for an improved management of  
318 marine and terrestrial production systems including: (i) promoting structurally complex patches  
319 of resources throughout the system, and species of particular concern for functional diversity, but  
320 (ii) controlling over-abundant and alien species and minimizing threatening ecosystem processes.  
321 Implementing those strategies will result in more heterogeneous production areas, with  
322 structurally more complex mosaics of habitats. The resulting production areas are likely to sustain  
323 higher levels of animal diversity and will be more resilient to external disturbances.

## 324 **The concept of agro-ecology as a sustainable and responsible way forwards**

325 Agro-ecology, a concept originally defined as “the application of ecological theory to the design  
326 and management of sustainable agricultural systems” (Altieri, 1987), has recently become a hot

327 topic with the aim to optimize economic, ecological, and social dimensions to achieve sustainable  
328 food production. Understanding the mechanisms underlying the resilience of agro-ecosystems is  
329 critical for conserving biodiversity and ecosystem functions in the face of disturbances (Moretti  
330 et al., 2006) and for securing the production of essential ecosystem services. Surprisingly, the  
331 majority of research on agro-ecology has been in done in plant production. This concept now calls  
332 scientists from animal ecology and animal production domains to readily interact by developing  
333 more interdisciplinarity.

334 Thus, five key ecological processes were proposed to be adapted to the animal context (Dumont  
335 et al., 2013): 1) adopting management practices, including breeding, to improve animal resilience  
336 and health; 2) decreasing the external inputs needed for production, particularly use of resources  
337 that are directly useable by humans; 3) decreasing pollution by optimizing the metabolic  
338 functioning of farming systems, including consideration of animal manure as a resource; 4)  
339 enhancing diversity within animal production systems to strengthen farm resilience, and 5)  
340 preserving biological diversity in agroecosystems.

341 Even if agro-ecosystem resilience has been considered as a key driver of sustainable agriculture  
342 under increasing environmental uncertainty, only a very few studies have explicitly tested the  
343 resilience of productivity to disturbance. Taking agroecology forward as a shared discipline needs  
344 a number of challenges to be overcome; these relate to scientific problems (Carlisle, 2014; Dumont  
345 et al., 2013) and cultural issues. From an ecologist perspective, agroecosystems are often seen as  
346 being a special case study that offers the opportunity to test ecological principles in conditions  
347 that are less complex and more clearly controlled than purely natural ecosystems. From the  
348 perspective of an animal production scientist, agroecology is often perceived as a constraint  
349 problem, i.e. how to achieve economic performance without breaking some environmental  
350 “rules”. An important objective to better understand the interactions between environmental and  
351 biological processes that control community resistance and resilience will be to move beyond  
352 these viewpoints and exploit the synergies that the biodiversity within agroecosystems can bring  
353 (Tabacchi et al., 2009). One example of a useful synergy is to view climatic events as manageable

354 phenomena resulting from processes whose effects could be much more mitigated through the  
355 use of integrated ecosystem management and flexible diversification than through adaptation to  
356 severe stress (Carlisle, 2014).

357 Thus, the notion of eco-efficiency may be a powerful tool (Keating et al., 2010). This implies  
358 enlarging traditional production-related efficiency definitions to include environmental (land,  
359 water, energy), ecological (biodiversity, resilience, conservation) and economic (labour, capital)  
360 dimensions. This eco-efficiency approach creates significant challenges for the integration of  
361 these multiple dimensions but there are promising avenues of research tackling this issue  
362 (Soteriades et al., 2016).

### 363 **The commonality in the use of advanced technologies to monitor animals**

364 Animal ecology and production science are both interested in explaining the variability with  
365 which individuals respond to their environment. These research fields, which both rely on  
366 methodologies to monitor animals in their living environment, have a lot to win from merging  
367 methodological approaches.

368 Recent technological advances allow ecologists studying free-ranging animals access to multiple  
369 parameters encompassing foraging patterns, social interactions, physiological parameters but  
370 also to environmental variables. These bio-logging technologies, recording from a distance several  
371 variables many times per seconds over periods up to years, now allow the quantification of  
372 energetic and behavioral variability between individuals (*e.g.* accelerometry, Gleiss et al., 2011).

373 Bio-logging is extensively used, as well, in animal production science and now recognized as field  
374 in its own right, in precision livestock farming (Wathes et al., 2008). It permits the monitoring of  
375 animals for signs of health problems, allowing timely intervention by the farm manager. The broad  
376 nature of the bio-logging data is increasingly useful, particularly with respect to phenotyping  
377 complex traits such as resilience and efficiency. Being able to achieve a sustainable balance  
378 between resilience and efficiency is a key goal of selection programs for agro-ecology. For  
379 instance, the efficiency with which farmed animals transfer energy towards body mass production  
380 could be evaluated from bio-logging measurements based on the time-budget devoted to feeding,

381 locomotion, sleeping or social interactions at a daily scale. Such proxy measurements allow the  
382 phenotyping of efficiency (and other complex traits) in large populations, and thereby open up for  
383 incorporation of such traits in genomic selection (e.g. [www.gentore/eu](http://www.gentore.eu)). From a husbandry  
384 perspective, finding fine-tuned modifications of farming environment to positively influence this  
385 productivity is also conceivable, e.g. detection of circadian optimal conditions in food access or  
386 ambient temperature. Those methodologies may change our view of how farmed animals are able  
387 to adapt their energy balance in response to changes in farming environments, as they did for wild  
388 animals or humans (Villars et al. 2012).

389 This offers the potential to integrate multiple markers over long-time scales to quantify factors  
390 affecting overall fitness. One promising step will be to combine diverse biomarkers to evaluate  
391 how environmental variations impact fitness and productivity over ages (a fundamental factor for  
392 selection in the wild) or over life stages (a key parameter to improve animal productivity). The  
393 use of non-invasive methodologies (using hairs, feathers, blood...) including biosensors raises the  
394 issue of integrating all this information in a valuable way. Consider for example animal resilience,  
395 the capacity to cope with short-term environmental fluctuations. There is no direct measure that  
396 encompasses all the facets of resilience, in other words it is a latent variable that can only be  
397 deduced by combining multiple (proxy) measures of its different aspects (see Højsgaard &  
398 Friggens, 2010 for a health-related example). This issue requires the development of new  
399 mathematical models on the ultimate consequence of, within and between individual differences  
400 in ecology (*e.g.* habitat use) and physiology (*i.e.* energy demands over different time scales).

401 An important challenge for ecology and animal production science is to safeguard animal welfare  
402 and thus health status across the wide range of husbandry and production environments, and also  
403 among individuals of different sizes and/or ages. This can range from the surveillance of animals  
404 scattered across very extensive rangelands to the monitoring of stress within groups in indoors  
405 environments. Currently, most protocols for welfare assessment rely on human observation (*i.e.*  
406 limited duration and potentially subjective). In this context, bio-logging technologies developed  
407 to be implemented in large or small animals have considerable potential to provide continuous

408 monitoring of welfare status, allowing early and rapid identification of changes in behavioral and  
409 physiological components (Borchers et al., 2016; Sadoul et al., 2014; Ripperger et al., 2016). We  
410 suggest that combining these different types of parameters offers a more complete way to  
411 quantify animal welfare, which better integrates animal coping ability to changing environments  
412 both in wild and farmed conditions.

413

#### 414 **Two topical examples of breaking down the interdisciplinary barriers**

415 Elaboration of the above points, and the commonalities that emerge, reinforces the call to more  
416 explicitly link these two disciplines for a better understanding of animals as systems, and animals  
417 within ecosystems. The importance of making such links, and the benefits arising, is illustrated  
418 by considering the following examples:

#### 419 CIRCULATION AND REASSORTMENT OF POTENTIAL ZONOTIC PATHOGENS BETWEEN WILD 420 AND DOMESTIC POPULATIONS

421 Historically, animal domestication has indirectly mediated the transfer of infectious agents  
422 between wildlife and humans (Morand et al., 2014). If cases of domestic emergence are not refuted  
423 (Pearce-Duvel, 2006), almost three-quarters of emerging infectious diseases significant in terms  
424 of public health originate in wild animals (Woolhouse et al., 2005). The recent outbreak of highly  
425 pathogenic avian influenza (HPAI) H5N8 clade 2.3.4.4 in both wild and domestic birds in Europe  
426 is a major example of the “round trips” of viruses between wild and domestic populations. The  
427 ancestor of the H5N8 virus was first identified in January 2014 in domestic poultry in South  
428 Korea., then adapted to wild migrating aquatic birds and rapidly spread in 2014–2015 (Lycett et  
429 al., 2016). This virus affected poultry worldwide from fall 2016 to spring 2017. It caused a few  
430 domestic cases in northern Europe, mainly in gallinaceous populations and more rarely in  
431 domestic or wild ducks and geese population, which are commonly resistant to HPAI. A H5N8-  
432 related virus appeared in June 2016 in Touva Republic (southern Siberia) causing high mortality  
433 in waterfowl (OIE 2016).

434 Crossing the species barrier favors transmission and circulation of pathogens and constitutes a  
435 major advantage for multi-host pathogens (generalists). Host switches rely on genetic changes  
436 including nucleotide substitutions, acquisition of mobile genetic elements, or important genome  
437 rearrangement through recombinations and reassortments. Influenza viruses are a remarkable  
438 example of genetic material exchange between viruses issued from domestic and wild animals.  
439 H5N8 is itself a long lasting descendant of the HPAI H5N1 virus, first detected in China in 1996  
440 and responsible for epizootics in domestic birds and some human cases since 2003 (Lycett et al.,  
441 2016). The complete sequence of the H5N8 Siberian strain isolated from wild birds in June 2016  
442 revealed many reassortments with other poultry viruses. This virus infected northern European  
443 wild and domestic whereas other reassortants infected birds in southern Europe birds in fall 2016  
444 to spring 2017 (Anses, 2017). The emergence of novel pathogenic strains within a region  
445 concentrating high densities of a receptive population (fat liver ducks) made possible (i) the  
446 dissemination of the virus within domestic and wild bird populations (abundant opportunities for  
447 cross-species transmission) and (ii) its reassortment with other low pathogenic strains of  
448 influenza virus circulating in the domestic and wild bird populations, thereby creating high levels  
449 of genetic diversity that can in turn broaden host-spectra.

450 Production of genetic variants is a mechanism predicted to favor the emergence of zoonotic  
451 strains. Fortunately, most of the time this has not led to pandemic viruses as avian influenza  
452 strains do not transfer easily from human to human due to the absence of important receptors in  
453 human bronchial tubes. Pigs are an exception to that as they are receptive to influenza viruses  
454 specific for pigs, humans and birds (Kaplan et al., 2017). As a consequence, when pigs are co-  
455 infected with viruses from different animal origins, they become gene reservoirs with the  
456 potential to facilitate reassortments and the emergence of pandemic viruses. Therefore,  
457 traditional farming systems mixing free range poultry and pigs in the same backyard close to  
458 human populations presents a risk for the emergence of new reassortants of influenza virus able  
459 to spread within human populations as pandemic viruses.

460 Together with emblematic examples of emerging and re-emerging vector-borne diseases in which  
461 wild and domestic animals play a key role as vectors, intermediate hosts and/or reservoirs  
462 (Boissier et al., 2016), influenza highlights the increasing globalization of health risks and the  
463 importance of the human-animal-ecosystem interface in the evolution and emergence of  
464 pathogens. It illustrates how a better knowledge of causes and consequences of certain human  
465 activities, lifestyles and behaviors in ecosystems is crucial for understanding disease dynamics  
466 and driving public policies. Therefore health security must be understood on a global scale  
467 integrating human health, animal health, plant health, ecosystems health and biodiversity. This  
468 ambition requires breaking down the interdisciplinary barriers that separate human and  
469 veterinary medicine from ecological, evolutionary and environmental science. It calls upon the  
470 development of integrative approaches linking the study of proximal factors underlying pathogen  
471 emergence and host physiological and adaptive responses to stress to their consequences on  
472 ecosystems functioning and evolution (Destoumieux-Garzón et al., 2018).

#### 473 THE ROLE OF ANIMALS IN THE ELEMENTARY CYCLES IN TERRESTRIAL AND AQUATIC 474 AGROECOSYSTEMS

475 Pushed by a dynamic political agenda on climate change, the roles of animals on biogeochemical  
476 cycles, the livestock sector contribution to global anthropogenic GHG emissions (14,5% of CO<sub>2</sub>,  
477 CH<sub>4</sub> and N<sub>2</sub>O emission) and mitigation options were highlighted (Gerber et al., 2013). This incited  
478 animal production research to collaborate with environment science. Initial studies were  
479 restricted to closed farm systems and animals were seen as “*a system*” emitting nutrients and  
480 gases in the atmosphere. Moreover, some effort was given to modelling nutrient emissions  
481 associated to waste management (Génermont et al., 1997), proposing some treatment options  
482 (Martinez et al., 2009) and practices (Thu et al., 2012).

483 However, this first era of research focussed on partial and segmented analysis of systems,  
484 neglecting more complex sets of interactions and flows between ecosystem compartments (not  
485 only exchanges with the atmosphere). Research somehow neglected the role of animals in

486 contributing to nutrient and carbon recycling to other compartments of the ecosystem like soil or  
487 crops, i.e. considering “*animals in their systems*”.

488 More recently there has been a marked increase of holistic and interdisciplinary research  
489 addressing biomass, nutrient and carbon recycling in soil-crop-animal systems at various scales,  
490 and their ecological, agronomic, environmental and economic impacts (Vayssières et al., 2009).  
491 Accordingly, animal science has adopted more holistic models, developing multi-dimensional  
492 impact assessment with metrics and methods derived from other disciplines including ecology,  
493 biogeochemistry, sociology and economics. Meanwhile, animal ecology and animal science have  
494 increasingly stressed the importance of considering the role of humans in their research, i.e.  
495 addressing sustainability and functioning of social ecological systems, a concept derived from new  
496 institutional economics (Ostrom, 2009).

497 In the terrestrial production context, research is now addressing animal effects on nutrient and  
498 carbon cycles in diverse agroecosystems. There are studies of the influence of specific  
499 management factors (e.g. ruminant grazing intensity) on nutrient recycling pathways, soil  
500 compaction and carbon stocks (de Faccio et al., 2010). In systems research on carbon balance, the  
501 use of pasture as the main source of feed was shown to be a non-negligible carbon sink under both  
502 semi-arid (e.g. Sahel) and humid environments (e.g. Amazonia) (Assouma et al., 2017; Stahl et al.,  
503 2016) addressed the importance of developing an ecosystem approach to better assess the real  
504 contribution of livestock. Enteritic methane from ruminants, emission from manure deposition,  
505 emission by termites, and savannah fire have been accounted for as well as carbon sink function  
506 of soils and perennial ligneous vegetation in an annual cycle. The carbon balance was ultimately  
507 found to be slightly negative, i.e. emissions due to livestock activities are compensated by carbon  
508 sequestration in soil and trees at landscape level. Thus, when environmental impact assessments  
509 integrate all the compartments of the agro-ecosystem (biomass, soil, plants and animals in  
510 relation to the atmosphere), and both emission and sequestration, the results contrast with partial  
511 analysis that classed African pastoral ecosystems as high GHG contributors.

512 In the aquatic production context, waste accounts for up to 75% of the nutrient discharge for  
513 Nitrogen and Phosphorus in conventional salmon and shrimp aquaculture. Therefore, biological  
514 and chemical filters have been developed to partially remove dissolved nutrients from waste.  
515 These various pathways of nutrient bioremediation have been increasingly embedded in diverse  
516 Integrated Multitrophic Aquaculture systems (IMTA), which are mostly adapted for land-based  
517 intensive aquaculture (fish, shrimp in ponds) (Troell et al., 2003). In such systems the addition of  
518 extractive organisms like seaweeds (macroalgae, culture of microalgae) (Milhazes-Cunha et al.,  
519 2017) or bivalves (shellfish) as biofilters to recycle wastewater, and reduce discharge and  
520 particulate and dissolved nutrient concentration was found promising (from 35 to 100% nitrogen  
521 removal). In open culture systems (fish cages) the setting up of IMTA is more complex and results  
522 are less clear. Accordingly, research is still on-going.

523 Such research needs continuity on the long term and design of new models (Lamprianidou et al.,  
524 2015). In particular, study of factors influencing reduction efficiency (seaweed species, capacity  
525 to uptake beyond physiological requirement, characteristics of production system and the  
526 environment, etc.) requires an interdisciplinary research approach (Troell et al., 2003). Similarly,  
527 increasing biomass recycling in terrestrial systems, or increasing carbon sequestration by soils  
528 and crops, is a long run and complex effort that argues for more global scientific collaboration.

## 529 **Conclusions**

530 This review highlights seven basic concepts that require cross-fertilization to respond to  
531 important societal challenges such as ecosystem resilience and farming sustainability. At the  
532 interface of animal ecology and animal production science, our article promotes an effective  
533 application of the agroecology concept to animals and the use of functional diversity to increase  
534 resilience in both wild and farmed systems. It also promotes the use of novel monitoring technologies  
535 to quantify animal welfare and factors affecting fitness. These measures are needed to evaluate  
536 viability risk, predict and potentially increase animal adaptability, and improve the management of  
537 wild and farmed systems, thereby responding to an increasing demand of the Society for the  
538 development of a sustainable management of systems

539 This ambition requires interdisciplinary research: we need a new era of translational research  
540 before application of results. Animal ecology has particular strengths in the study of interactions  
541 between species, biodiversity, adaptive evolution in natural populations and ecosystem resilience.  
542 Animal production science has disciplinary strengths in selective breeding, production chains,  
543 economics and management. Therefore the two disciplines have many complementary skills but  
544 a stronger synergy is lacking due to old habits, i.e. perceived differences in viewpoints on the goal  
545 of each discipline, different knowledge and scientific vocabulary (e.g. in quantitative genetics), and  
546 different policy masters. Nevertheless, there are substantial advantages to be gained for animal-  
547 related research and for society's interaction with animals, from an enhanced cross-fertilization  
548 between disciplines.

549 Modelling approaches have the power to integrate disciplinary visions and knowledge and to  
550 translate them into actionable research. However, so far, research has not reached the level of  
551 operability required to fully "pilot" animal systems and agroecosystems and has often socio  
552 economic factors and innovation processes, which hampers the adoption of any proposed  
553 changes. Integration of knowledge holders from the society in the process of research is also  
554 needed to tackle anticipated challenges at the interface between science, policy and society. This  
555 needs the development of knowledge integration techniques and enhanced collective expertise  
556 backed by participatory modelling and science. Such a process begins by breaking down the  
557 disciplinary boundaries. Substantial advantages will be gained for animal science, and for society's  
558 interaction with animals, from cross-fertilization between the animal ecology and animal  
559 production science disciplines. This should be accompanied by scientific vision, programs and  
560 policy tools that reverse the fragmentation of animal research across other themes, and instead  
561 create critical mass for animal science. The analogy to the emergence of One Health seems highly  
562 relevant, it is time for One Animal-Research Kinship, one ARK!!

563

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568