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1 **POSITION PAPER**

2

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

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27

28 **Summary**

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

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

43 3. The need for breaking down interdisciplinary barriers is illustrated by two representative
44 examples: i) the circulation and reassortment of pathogens between wild and domestic animals
45 and ii) the role of animals in nutrient cycles; i.e. recycling nitrogen (N), phosphorus (P), and
46 carbon (C) through, for example, contribution to soil fertility and carbon sequestration.

47 4. Our synthesis identifies the need for knowledge integration techniques supported by
48 programs and policy tools that reverse the fragmentation of animal research towards a
49 unification into a single Animal Research Kinship, OneARK, which sets new objectives for future
50 science policy.

51 5. At the interface of animal ecology and animal production science, our article promotes an
52 effective application of the agroecology concept to animals and the use of functional diversity to
53 increase resilience in both wild and farmed systems. It also promotes the use of novel

54 monitoring technologies to quantify animal welfare and factors affecting fitness. These measures
55 are needed to evaluate viability risk, predict and potentially increase animal adaptability, and
56 improve the management of wild and farmed systems, thereby responding to an increasing
57 demand of society for the development of a sustainable management of systems.

58

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

61

62 **Introduction**

63 Our planet is undergoing major global environmental changes mainly caused by a rapid increase
64 in human population and the concomitant agriculture industrialisation (specialization,
65 concentration, intensification). These changes have a profound impact on biodiversity, on land
66 use due to modified resource availability, as well as on emergence and spatial distribution of
67 pathogens (Keesing et al. 2010). A primary concern is the extremely rapid rate of these changes,
68 which apply strong and often novel selective pressures on animals, at rates rarely encountered
69 over evolutionary time scales. These challenges are placing new demands on physiological and
70 adaptive capacities (particularly phenotypic plasticity which allows for the compensation of
71 rapid environmental changes when genetic adaptation is too slow), on the interactions among
72 species, and ultimately on species persistence and biodiversity. The consequences are major in
73 terms of conservation of biodiversity but will also have impacts on every category of ecosystem
74 services: support (e.g. soil formation), production (e.g. milk, eggs and meat), regulation (e.g. pest
75 control) and cultural, or on their combination (e.g. biodiversity-related ecotourism (Fuller et al.,
76 2007). Thus, we have a responsibility to find new ways to better understand and preserve the
77 functional diversity of ecosystems. These have been, and will continue to be, a major support of
78 human endeavours.

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

87 It is increasingly recognized that there is a continuum between animals in managed ecosystems
88 and animals in natural environments. No production system whatever its level of biosecurity is

89 completely isolated from the surrounding environment. Likewise, today, no ecosystem is
90 completely isolated from human influence, and increasingly ecosystems are subject to some
91 degree of human management, or have limits imposed on them by human activity. Therefore, it
92 is highly relevant to consider what the cross-fertilisation between the two communities of
93 animal production science and animal ecology can bring.

94 A number of basic concepts appear at first sight to be fundamentally different between animal
95 production science and ecology. However, when these concepts are given due consideration it
96 transpires that they are actually more similar and not really in opposition. The aim of this paper
97 is to explore the common points between animal production science and animal ecology. Better
98 recognizing the similarities between the two communities will identify promising avenues of
99 synergy by concept and/or methodology transfers between communities. We first discuss seven
100 topics that are common to both communities but viewed from differing perspectives, in order to
101 show their potential for synergy and then highlight these points using two examples. This
102 prospective thinking for a community unification into a single Animal Research Kinship, i.e.
103 OneARK, sets new objectives for future science policy.

104 **Artificial selection versus natural selection**

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

112 Natural selection can act simultaneously on multiple traits, so that trade-offs are an important
113 part of understanding adaptation and response to selection: natural selection maximises average
114 fitness of the population, not trait values (Stearns, 1977). Another fundamental aspect is that
115 natural selection varies spatially and temporally depending on the environment (Siepielski et al.,

116 2013, 2017) so that traits may be positively selected in one environment and counter-selected in
117 another. Investigating selection is thus complex notably because we need to assess the actual
118 target of selection but also make sure that the covariances between trait and fitness are not only
119 due to environmental covariance (Morrissey et al., 2010).

120 It is generally admitted that artificial selection started in the early stages of domestication, the
121 first selected traits being favourable to the domestication process itself, e.g. docility. During the
122 last three centuries, and especially during the last six decades, this artificial selection has
123 become and more organized and intense, targeting and maximising specific traits (e.g. dairy
124 production, growth rate). Another consequence of domestication was to decrease the natural
125 selection pressure because humans increasingly controlled the environment of animals. This is
126 typified by the strong intensification of animal production.

127 After domestication, selection in different places and with different goals first led to a huge
128 increase in diversity between populations (Darwin, 1859). However, the recent changes in
129 livestock breeding led to the opposite, with (i) a decrease in the number of breeds for a given
130 species (Sherf, 2000) and (ii) a reduction of within-population genetic variability in intensively
131 selected populations (Danchin-Burge et al., 2012), which means a lower adaptive potential in the
132 long run. In the short run, this selection of highly specialised and rather homogeneous “elite”
133 breeding animals led to (i) the unwanted evolution of some functional traits due to unfavourable
134 genetic correlations (e.g. milk yield and female fertility) (Oltenacu & Broom, 2010) and (ii)
135 reduced robustness and flexibility *i.e.*, lower resilience to environmental variability, particularly
136 to new stress and disease challenges. The multivariate nature of selection acknowledged by
137 animal ecologists (Lande & Arnold, 1983) has promoted the development of artificial selection
138 programs which include the use of selection on multiple traits (Puillet et al., 2016). Indeed,
139 current livestock selection programs are increasingly seeking to optimise animal fitness in the
140 production environment by putting more emphasis on functional traits and including robustness
141 and adaptability traits alongside production (Berghof et al., 2019). Taking into account such

142 trade-offs is particularly important in the context of global changes where resource availability
143 and variability will be strongly affected.

144 Such collaborative efforts are increasingly needed because the rapid and strong changes of
145 environmental conditions generate strong selective pressures, so much so that humans are now
146 considered as the greatest evolutionary force (Palumbi, 2001; Sarrazin et al 2016).
147 Understanding how populations respond to these new selective pressures, which means
148 understanding the inter-relationships between rates of environmental change and the selection
149 pressure this exerts on animal populations, is a key issue in applied evolution and conservation
150 (e.g. Siepielski et al. 2017). It is also a key issue for artificial selection since global changes are
151 altering the environmental conditions under which artificial selection is operating. For example,
152 because genotypes can perform differently under different environmental conditions (gene by
153 environment interactions, G*E) there is a strong risk that individuals with high breeding values
154 for production traits in protected environments will tend to be negatively impacted by adverse
155 environments, leading to poorer breeding values for those animals that are most
156 environmentally sensitive. Conversely, animals with poorer breeding values for production
157 traits may be the individuals best equipped to deal with environmental perturbations, so that
158 the selection criteria ought to be multivariate and in multiple environments. Animal ecology will
159 benefit from the rapid advances in quantifying the genetic bases of phenotypic/performance
160 robustness of animals to environmental variability (quantitative genetics, epigenetic regulation),
161 a field that is likely to advance much more rapidly in animal production science because of
162 easier access to controlled genetic materials, advanced control of environmental backgrounds,
163 rapid expansion of multivariate massive phenotyping (including omics), and the ability to
164 account for social interactions between conspecifics (Wade et al. 2010). A major challenge is to
165 understand how global environmental changes are going to affect selective pressures acting on
166 both wild and domesticated populations. Determining the theoretical bases of how natural and
167 artificial selections actually modulate adaptive (and therefore, sustainable) responses of these
168 populations to these new selective pressures is a corner-stone objective. This will pave the way

169 of resolving how we may improve (i) our management of agro- and wild ecosystems by
170 increasing biodiversity and/or within populations' genotypic/phenotypic diversity, (ii) thereby
171 improving resilience capacity of individuals, populations, and systems, and (iii) reducing
172 viability-risks of our farmed and wild environments.

173

174 **Viability risks for farmed systems versus natural ecosystems**

175 Global changes pose a viability risk for both natural and farmed systems, although the
176 "currencies" by which viability is judged have traditionally differed; it is largely about economics
177 for farmed systems and about biodiversity and population persistence for natural ecosystems.
178 The framework of ecosystem services links both types of systems by considering them as
179 essential for sustainable development, but viability of natural populations for their own sake
180 also needs to be integrated (Martin et al 2016).. The most commonly used currency to assess
181 viability in wild populations is the probability of extinction of a population over an arbitrarily
182 chosen time period (e.g. 100 years in the UICN red list) or the median time to extinction. Several
183 components of global change will affect viability of both natural and farmed systems.

184 The impacts of climate change emerge through both long-term changes in average conditions
185 within local environments and an increase in the frequency of extreme events (Ummenhofer &
186 Meehl, 2017). The former has received more attention so far. The effects of climate change can
187 be mediated through many indirect effects such as the disruption of interaction between species
188 because of changes of phenology or morphology (van Gils et al., 2016). A typical example is the
189 earlier breeding of insectivorous birds so that the peak of offspring energetic needs coincides
190 with the peak of food abundance (caterpillars, Visser et al., 1998): if the timing is mismatched
191 then breeding success is low. These effects are more likely to be encountered in wild than
192 farmed system where long-term changes in average environmental conditions will more
193 frequently be experienced in terms of direct effects that alter resource availability. In farmed
194 systems, the impact on animals will be less direct but in the longer term will impact farm
195 management systems e.g. impacting the stocking densities of animals that are sustainable in

196 extensive systems, and incurring greater costs for intensive systems (e.g. cooling systems). In
197 managed populations, extreme events such as drought or flooding require the farmer to make
198 costly, unplanned interventions (buying food, transporting animals) where possible. These
199 clearly have economic consequences especially if possible interventions are limited and loss of
200 animals occurs (e.g. rangeland grazing). In wild populations, effects of extreme events include
201 both decreased survival (e.g. die-offs, McKechnie & Wolf, 2010) and reduced breeding success
202 (Jenouvrier et al., 2015). Extreme events may generate very strong selection pressures leading
203 to marked evolutionary shifts in wild populations (Grant et al., 2017). However, the impact of
204 extreme events is particularly complex to anticipate, as they engage non-linear shifts in multi-
205 species interactions.

206 **Introduced exotic species**, which may be pathogens, pathogen carriers, predators or directly
207 competing species, represent another major viability risk to both farmed and wild populations
208 (Bellard et al., 2016; Paine et al., 2016; see section on circulation of zoonotic pathogens). They
209 are likely to be more prevalent and successful in highly anthropized habitats such as peri-urban
210 and agricultural lands, and species of tropical origin benefit from the warming climate in
211 temperate and boreal regions (Hufbauer et al 2012, Bellard et al. 2013).

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

220 There are also viability risks due to rigidity of human behavior. For wild animals, one example is
221 how human habits of farming landscape may evolve in response to recolonization by wild
222 animal species like large carnivores, a question for which some straightforward solutions may

223 exist (Kuijper et al. 2019). In farming, an example of rigidity of human behavior is the continued
224 use of inappropriate animal genetics through a failure to recognize the traits needed for
225 sustainability in new conditions. Indeed, the loss of genetic diversity of domesticated breeds due
226 to rigid selection of a very few breeds is a major issue being addressed by the FAO (FAO, 2015).
227 Rigidity in farm management, such as failing to adapt fodder cropping practices to changing
228 seasonal patterns, can also increase the viability risks for the animals that depend on this fodder.
229 Rigidity of behaviour can apply not just to humans but also to animal species when one
230 considers differences between generalist/specialist or plastic/non-plastic species (Clavel et al.,
231 2011). For example, one issue is the existence of ecological traps where species respond to cues
232 that were supposed to signal a high quality environment but that got uncorrelated from this
233 environment, such as asphalt roads that may reflect light in the same manner as water bodies
234 attracting some insects to breed (Schlaepfer et al., 2002). Ultimately, population viability will
235 depend on the ability of organisms to respond adaptively to complex environmental changes
236 inducing novel selective pressures.

237 Both farmed and wild populations share some of the same viability risks and ultimately must
238 respond by adaptation (microevolution and/or plasticity). The degree of management of the
239 animal populations within a given ecosystem will mainly affect the extent to which risks can be
240 buffered by human intervention, e.g. deploying reproductive technologies developed in animal
241 production science to aid in rewilding and to overcome habitat fragmentation. Biodiversity and
242 economics are connected across the spectrum from farmed to natural ecosystems. Tools
243 developed at the frontier between ecology and economics, such as coviability analyses
244 (Mouysset et al., 2014), which aim at finding compromises where viability of both farmed and
245 natural systems can co-exist by coupling economic and biodiversity models, will be important
246 for the future.

247 **Agro-ecosystems and farmed animal management versus ecosystems and wild**
248 **animal management**

249 In contrast to wild animals in natural ecosystems that are fully in interaction with the
250 environment, the magnitude of interactions of farmed animals with the environment covers a
251 spectrum, ranging from agro-ecosystems to landless livestock production. This gradient is
252 driven by the form of the feeding system, ranging from land sharing to land sparing, and the
253 level of interaction the livestock population has *vis-a-vis* agricultural and natural system
254 components (crops, forest, water, wildlife, etc.). Livestock agro-ecosystems are defined by a high
255 dependence of livestock on local resources, like land and water (pastoralism being its apogee).
256 At the opposite end of the scale, landless livestock systems maximize their direct independence
257 from environmental constraints by means of feed trade, thus establishing production systems
258 with almost no direct relation (excluding by the market) between the places and times where
259 livestock are reared, where their feed is produced, and where their products are consumed.

260 Gradients in degree of human intervention are also a common element of wild animal and
261 natural ecosystem management. Indeed, not a single natural ecosystem is human-proof, at least
262 since climate change started. More direct wild animal ecosystem management profiles can range
263 from biodiversity reserves through natural parks, run as wildlife sanctuaries, to wildlife areas
264 managed by local communities, which recognize combined wildlife, livestock, and rangeland
265 services as essential for human groups, a vision emphasized in Southern Africa (Chomba et al.,
266 2014; Jones et al., 2015).

267 In the latter case there is a strong interaction between agricultural activity and ecosystem
268 management. More generally, the frontier between the “wild” and the “farmed” animals is
269 progressively being eroded, changing to situations where more coexistence and interactions are
270 inevitable if we wish to reconcile preserving biodiversity and better resource sustainability.

271 Achieving this in the design of these re-expanding agro-ecosystems imposes a tightening of the
272 collaboration between animal production scientists and animal ecologists to reconcile opposing
273 interests. Some examples of this are studies on heathlands or the policy of “Natura 2000” to
274 preserve biodiversity in Europe, often in human-made ecosystems. The governance mode of
275 Natura 2000 brings together land users and civil society in decision making. it also includes both

276 animal scientists and animal ecologists on its scientific committees, valuing their role in
277 providing evidence through qualitative and quantitative evaluation of benefits, i.e. finding the
278 balance between provisioning services to local farming systems, and markets, and conservation
279 services to the society (McCauley, 2008, Morán-Ordóñez et al., 2013). Furthermore, and in line
280 with societal considerations, there is a visible shift in livestock and wildlife policy dialogue,
281 moving beyond the simple support of resource sufficiency and food provision to now provide
282 incentives for conservation and rehabilitation of functional integrity, and payment for
283 environment services in production areas, and at a global Earth scale (Frost et al., 2008; Kampli
284 et al., 2011). Both animal ecology and animal production scientists are then forced to converge
285 when it becomes time to inform politics and the society about solutions to reach the sustainable
286 development objectives (e.g. McCauley, 2008).

287 **The key role of animal adaptability to connect evolutionary and animal** 288 **production sciences**

289 Adaptation processes are multifaceted, taking place at different biological levels with different
290 temporal modalities (Gould & Lloyd, 1999). Evolutionary biologists, who mainly deal with
291 natural populations, have focused on adaptation as a trait increasing relative fitness, *i.e.* which
292 evolved via natural selection. Physiologists, who deal with laboratory and farmed strains, have
293 focused on within lifetime reversible processes that allow individuals to adjust to their
294 environment, with less focus on their heritability. These biological processes depend on the
295 variability of the environment and adaptation can be described by the following continuum: (i)
296 phenotypic flexibility of individuals leading to temporary/reversible changes, (ii) developmental
297 plasticity leading to more permanent changes of phenotypes through physiological and/or
298 epigenetic mechanisms, and (iii) intergenerational modification of allele frequencies through
299 natural selection (Chevin & Beckerman, 2011). Integrating these different adaptive mechanisms
300 has to be developed together at the interface with animal production science. Studying
301 performance and behavioral changes induced by modifications in the farming environment
302 would provide a great opportunity for evolutionary biologists to investigate the key mechanisms

303 allowing individuals to maintain their performances over different abiotic conditions,
304 complementing and providing a bridge between approaches in the lab and in the wild.

305 The complex phenotypes underlying adaptability are forcing scientists to develop an integrated
306 approach looking at multiple characters. The recent expansion of genomics, and other -omic
307 data, offers new avenues to understand the mechanisms that shape adaptability (Valcu &
308 Kempenaers, 2014). Studying organisms as a whole, taking into account functional links
309 between traits is now made possible by combining -omic data with the characterization of
310 physiological and performance traits (Prunet et al., 2012). This should uncover cell or
311 physiological processes important for adaptability in both wild and farmed animals. However,
312 such approaches often produce complex data on cell and physiological pathways that are
313 concomitantly affected. Building an integrated phenotyping (Headon, 2013) that sorts the
314 mechanisms underlying adaptability in order of importance now needs to combine biological
315 knowledge of the processes involved, bioinformatics, and statistical knowledge.

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

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

329 **The importance of animal diversity for system resilience**

330 Ecological resilience focuses on the adaptive capacity of an ecosystem and is defined as the
331 amount of disturbance this system can absorb while remaining within the same stability range
332 and retaining the same function(s), achieved through reinforcing within-system structures,
333 processes and reciprocal feedbacks (Holling, 1996; Kaarlejärvi et al., 2015; Gladstone-Gallagher
334 et al., 2019).

335 Resilience strongly depends on the initial composition of the local ecological assemblage and the
336 degree of disturbance (Sasaki et al., 2015). In highly disturbed areas, differences in the recovery
337 trajectory of assemblages have been related to differences in the composition and the dispersal
338 capacities of the surrounding species pool of colonists and the level of connectivity among
339 populations, species and ecosystems (Allison, 2004). These factors influence both probability of
340 species persistence by increasing the genetic diversity of local populations (Bach & Dahllöf,
341 2012) and capacity for recovery by providing sources of propagating organisms (de Juan et al.,
342 2013).

343 Biodiversity, a key factor for improving the long-term resilience of ecosystems (Awiti, 2011;
344 Mori et al., 2013; Oliver et al., 2015), is frequently associated with high functional redundancy
345 (*i.e.* presence of several species able to perform similar functions) (Sasaki et al., 2015; Kaiser-
346 Bunbury et al., 2017) and high species complementarity (Lindegren et al., 2016). Both taxonomic
347 (TD) and functional (FD) diversities, but not species richness, adequately capture the aspects of
348 biodiversity most relevant to ecosystem stability and functionality (Mori et al., 2013). TD
349 enhances resilience because most of the rare species within an assemblage are considered as
350 functionally similar to the dominant ones and able to compensate their potential loss under
351 changing environmental conditions, thus maintaining ecosystem functions. However, the
352 maintenance of a particular assemblage is not a necessary requirement for the resilience of
353 ecosystem functions (Oliver et al. 2015). Functions could be resistant to change or recovered
354 following disturbance with taxonomically different assemblages of species, while exhibiting
355 rather similar sets of traits (Gladstone-Gallagher et al. 2019) or maintaining interactions with
356 sufficient resemblance to the previous system so as to allow it to be recognizably similar

357 (Bregman et al., 2017). FD improves resilience because a more diverse set of traits increases the
358 variety of potential responses to disturbance (Messier et al., 2019). This then increases the
359 likelihood that species can compensate function(s) lost during disturbance events (Moretti et al.,
360 2006; Kühnel & Blüthgen, 2015). However, resilience is also likely to be scale-dependent
361 (Shippers et al., 2015; Gladstone-Gallagher et al., 2019), *i.e.* a combination of traits providing
362 resilience to small-scale disturbance can be ineffective against disturbance acting at largest
363 scale. As a result, the link between biodiversity and resilience is sometimes weak (Bellwood et
364 al., 2003). If the trait structure of highly diverse animal assemblages remains rather stable after
365 moderate stress, further intensification of human pressure can substantially reduce the variety
366 of traits and results in significant alteration of functional diversity (Bregman et al., 2017). This
367 raises the question of how to manage resilience and ecosystem services (*i.e.* the varied benefits
368 that humans freely gain from the natural environment and from properly-functioning managed
369 ecosystems, including provisioning, regulating, cultural and habitat and ecosystem functioning
370 services) in socio-ecological systems?

371 Conceptual frameworks, tools and indicators (Sasaki et al., 2015; Oliver et al., 2015) have been
372 defined for quantifying the resilience of coastal fisheries, estuaries or agricultural landscapes (de
373 Juan et al., 2013; Mijatović et al., 2013) based on structural and functional attributes; *e.g.*
374 ecosystem elasticity or sensitivity and adaptive capacity (López et al., 2013). Trends in the
375 frequency of animal species that provide key ecosystem functions in Great Britain, have
376 highlighted that they are not equally impaired by global change, and conservation actions should
377 focus on the functional groups for which there is clear evidence of resilience erosion (Oliver et
378 al., 2015). Moreover, community field experiments have clearly shown that vegetation
379 restoration can improve pollination, suggesting that the degradation of ecosystem functions is at
380 least partially reversible (Kaiser-Bunbury et al., 2017) and that severe disturbance-driven
381 reduction in ecosystem function does not preclude rapid ecosystem recovery, at least when the
382 ecosystem has not been pushed beyond a tipping point.

383 Several pattern- or process-oriented strategies have been suggested (Pauly et al., 2002; Fischer
384 et al., 2006) to enhance biodiversity and ecosystem resilience for an improved management of
385 marine and terrestrial production systems including: (i) promoting structurally complex patches
386 of resources throughout the system, and species of particular concern for functional diversity,
387 but (ii) controlling over-abundant and alien species and minimizing threatening ecosystem
388 processes. Implementing those strategies will result in more heterogeneous production areas,
389 with structurally more complex mosaics of habitats. The resulting production areas are likely to
390 sustain higher levels of animal diversity and will be more resilient to external disturbances.

391 The concept of animal diversity can be applied in various ways within livestock farming systems.
392 A first aspect of animal diversity is the diversity of species, with for instance a mixed farm
393 exploiting sheep and cattle or an aquaculture farm exploiting different fish species. The benefit
394 of species diversity in the farm is generally based on the ability of various species to exploit
395 different resources. Sheep and cattle in grazing systems are using different patches of grass, with
396 different plants favoured by the different selection strategies. The same type of
397 complementarity is used in recirculated aquaculture systems with fish that feed in different
398 levels of the water column. Complementarity of species can also go beyond complementarity of
399 resources used, with farming systems based on the complete trophic chain such as integrated
400 multi-trophic aquaculture systems (IMTA). The benefit of species diversity in a farm can also
401 rely on the diversity of products that are commercialized. For instance, small ruminants can be
402 used as cash flow while larger ruminants have a role of savings.

403 A second aspect of animal diversity is the diversity of individuals of the same species. Animals
404 may be diverse in terms of their adaptive profiles, with for instance a type of cow that copes with
405 heat stress and another type that copes with feed shortage. Having these two types of
406 individuals in a herd can enlarge the range of perturbations that the livestock system can absorb,
407 and thereby increase the resilience of system. Animals can also be diverse in terms of their
408 lifetime trajectories, with for instance females that have different types of reproductive rhythms

409 (e.g. extended lactation in dairy production, accelerated lambing in sheep production). This
410 diversity of trajectories within the herd can be useful to cope with environmental challenges
411 (portfolio effect) or to have different types of products answering to different market needs (e.g.
412 heavy/light lambs).

413

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

415 Agro-ecology, a concept originally defined as “the application of ecological theory to the design
416 and management of sustainable agricultural systems” (Altieri, 1987), has recently become a hot
417 topic with the aim to optimize economic, ecological, and social dimensions to achieve
418 sustainable food production. Understanding the mechanisms underlying the resilience of agro-
419 ecosystems is critical for conserving biodiversity and ecosystem functions in the face of
420 disturbances (Moretti et al., 2006) and for securing the production of essential ecosystem
421 services. Surprisingly, the majority of research on agro-ecology has been in done in plant
422 production. This concept now calls scientists from animal ecology and animal production
423 domains to readily interact by developing more interdisciplinarity.

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

431 Even if agro-ecosystem resilience has been considered as a key driver of sustainable agriculture
432 under increasing environmental uncertainty, only a very few studies have explicitly tested the
433 resilience of productivity to disturbance. Taking agroecology forward as a shared discipline
434 needs a number of challenges to be overcome; these relate to scientific problems (Carlisle, 2014;

435 Dumont et al., 2013) and cultural issues. From an ecologist perspective, agroecosystems are
436 often seen as being a special case study that offers the opportunity to test ecological principles in
437 conditions that are less complex and more clearly controlled than purely natural ecosystems.
438 From the perspective of an animal production scientist, agroecology is often perceived as a
439 constraint problem, i.e. how to achieve economic performance without breaking some
440 environmental “rules”. An important objective to better understand the interactions between
441 environmental and biological processes that control community resistance and resilience will be
442 to move beyond these viewpoints and exploit the synergies that the biodiversity within
443 agroecosystems can bring (Tabacchi et al., 2009; Tixier-Boichard et al., 2015). One example of a
444 useful synergy is to view climatic events as manageable phenomena resulting from processes
445 whose effects could be much more mitigated through the use of integrated ecosystem
446 management and flexible diversification than through adaptation to severe stress (Carlisle,
447 2014).

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

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

455 In the context of agro-ecology, understanding the variability with which individuals respond to
456 their environment is a key entry point for understanding most of the issues raised above.
457 Similarly, study of this variability also help to assess animal welfare at individual level, an issue
458 which is now a necessary respond to the societal demand to improve animal welfare. Animal
459 ecology and production science are both interested in explaining the variability with which
460 individuals respond to their environment and have a lot to win from merging methodological
461 approaches for quantifying this variability.

462 Recent technological advances allow ecologists studying free-ranging animals access to multiple
463 parameters encompassing foraging patterns, social interactions, physiological parameters but
464 also to monitor environmental variables or entire ecological communities (e.g; Rutz and Hays,
465 2019). These bio-logging technologies, recording from a distance several variables many times
466 per seconds over periods up to years, now allow the quantification of energetic and behavioral
467 variability between individuals (*e.g.* accelerometry, Gleiss et al., 2011).

468 Bio-logging is extensively used, as well, in animal production science and now recognized as
469 field in its own right, in precision livestock farming (Wathes et al., 2008). It permits the
470 monitoring of animals for signs of health problems, allowing timely intervention by the farm
471 manager. The broad nature of the bio-logging data is increasingly useful, particularly with
472 respect to phenotyping complex traits such as resilience and efficiency. Being able to achieve a
473 sustainable balance between resilience and efficiency is a key goal of selection programs for
474 agro-ecology. For instance, the efficiency with which farmed animals transfer energy towards
475 body mass production could be evaluated from bio-logging measurements based on the time-
476 budget devoted to feeding, locomotion, sleeping or social interactions at a daily scale. Such proxy
477 measurements allow the phenotyping of efficiency (and other complex traits) in large
478 populations, and thereby open up for incorporation of such traits in genomic selection (e.g.
479 www.gentore/eu). From a husbandry perspective, finding fine-tuned modifications of farming
480 environment to positively influence this productivity is also conceivable, e.g. detection of
481 circadian optimal conditions in food access or ambient temperature. Those methodologies may
482 change our view of how farmed animals are able to adapt their energy balance in response to
483 changes in farming environments, as they did for wild animals or humans (Villars et al. 2012).

484 This offers the potential to integrate multiple markers over long timescales to quantify factors
485 affecting overall fitness. One promising step will be to combine diverse biomarkers to evaluate
486 how environmental variations impact fitness and productivity over ages (a fundamental factor
487 for selection in the wild) or over life stages (a key parameter to improve animal productivity).

488 The use of non-invasive methodologies (using hairs, feathers, blood...) including biosensors

489 raises the issue of integrating all this information in a valuable way. Consider for example animal
490 resilience, the capacity to cope with short-term environmental fluctuations. There is no direct
491 measure that encompasses all the facets of resilience, in other words it is a latent variable that
492 can only be deduced by combining multiple (proxy) measures of its different aspects (see
493 Højsgaard & Friggens, 2010 for a health-related example). This issue of accessing latent
494 variables from multiple proxies is the focus of much research using signal processing methods,
495 and will be extremely useful for quantifying the ultimate consequences of within and between
496 individual differences in ecology (*e.g.* habitat use) and physiology (*i.e.* energy demands over
497 different time scales).

498 An important challenge for ecology and animal production science is to safeguard animal
499 welfare and thus health status across the wide range of husbandry and production
500 environments, and also among individuals of different sizes and/or ages. This can range from
501 the surveillance of animals scattered across very extensive rangelands to the monitoring of
502 stress within groups in indoors environments. Currently, most protocols for welfare assessment
503 rely on human observation (*i.e.* limited duration and potentially subjective). In this context, bio-
504 logging technologies developed to be implemented in large or small animals have considerable
505 potential to provide continuous monitoring of welfare status, allowing early and rapid
506 identification of changes in behavioral and physiological components (Borchers et al., 2016;
507 Sadoul et al., 2014; Ripperger et al., 2016). We suggest that combining these different types of
508 parameters offers a more complete way to quantify animal welfare, which better integrates
509 animal coping ability to changing environments both in wild and farmed conditions.

510

511 **Two topical examples of breaking down the interdisciplinary barriers**

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

516 CIRCULATION AND REASSORTMENT OF POTENTIAL ZONOTIC PATHOGENS BETWEEN
517 WILD AND DOMESTIC POPULATIONS

518 Historically, animal domestication has indirectly mediated the transfer of infectious agents
519 between wildlife and humans (Morand et al., 2014). If cases of domestic emergence are not
520 refuted (Pearce-Duvet, 2006), almost three-quarters of emerging infectious diseases significant
521 in terms of public health originate in wild animals (Woolhouse et al., 2005). The recent outbreak
522 of highly pathogenic avian influenza (HPAI) H5N8 clade 2.3.4.4 in both wild and domestic birds
523 in Europe is a major example of the “round trips” of viruses between wild and domestic
524 populations. The ancestor of the H5N8 virus was first identified in January 2014 in domestic
525 poultry in South Korea, then adapted to wild migrating aquatic birds and rapidly spread in
526 2014–2015 (Lycett et al., 2016). This virus affected poultry worldwide from fall 2016 to spring
527 2017. It caused a few domestic cases in northern Europe, mainly in gallinaceous populations and
528 more rarely in domestic or wild ducks and geese population, which are commonly more
529 resistant to HPAI. A H5N8-related virus appeared in June 2016 in Touva Republic (southern
530 Siberia) causing high mortality in waterfowl (OIE 2016).

531 Crossing the species barrier favors transmission and circulation of pathogens and constitutes a
532 major advantage for multi-host pathogens (generalists). Host switches rely on genetic changes
533 including nucleotide substitutions, acquisition of mobile genetic elements, or important genome
534 rearrangements through recombinations and reassortments. Influenza viruses are a remarkable
535 example of genetic material exchange between viruses issued from domestic and wild animals.
536 H5N8 is itself a long lasting descendant of the HPAI H5N1 virus, first detected in China in 1996
537 and responsible for epizootics in domestic birds and some human cases since 2003 (Lycett et al.,
538 2016). The complete sequence of the H5N8 Siberian strain isolated from wild birds in June 2016
539 revealed many reassortments with other poultry viruses. This virus infected northern European
540 wild and domestic whereas other reassortants infected birds in southern Europe birds in fall
541 2016 to spring 2017 (Anses, 2017). The emergence of novel pathogenic strains within a region
542 concentrating high densities of a receptive population (fat liver ducks) made possible (i) the

543 dissemination of the virus within domestic and wild bird populations (abundant opportunities
544 for cross-species transmission) and (ii) its reassortment with other low pathogenic strains of
545 influenza virus circulating in the domestic and wild bird populations, thereby creating high
546 levels of genetic diversity that can in turn broaden host-spectra. This example of massive
547 spreading of a wildlife virus within a domestic population is emblematic of the risk induced by
548 massive change in “traditional” production methods. Thirty years ago, the traditional fat liver
549 duck production involved small rearing farms (around 1000 free range ducks within rearing
550 period) and force feeding was operated by so-called “electrical force feeders” which enabled a
551 single operator to force feed only 200 birds a day. The appearance and spreading of ‘pneumatic
552 force feeders” during the end of the 90’s, enabled a single operator to force feed around 1000
553 ducks a day. The enhanced productivity promotes a higher consumer demand for a lower price
554 fat liver. It also increases the rearing production of ducks with a number of birds per flock
555 frequently higher than 10 000 and with a higher density of ducks in the free-range pens. These
556 increases in number and density of susceptible birds (without recourse to special sanitary
557 protection measures) are certainly risk factors for a higher spreading of avian influenza.

558 Production of genetic variants is a mechanism predicted to favor the emergence of zoonotic
559 strains and is difficult to prevent but could be minimized by avoiding passages of the virus from
560 bird to bird or between animal species. Fortunately, most of the time this has not led to
561 pandemic viruses as avian influenza strains do not transfer easily from human to human due to
562 the absence of important receptors in human bronchial tubes. Pigs are an exception to that as
563 they are receptive to influenza viruses specific for pigs, humans and birds (Kaplan et al., 2017).
564 As a consequence, when pigs are co-infected with viruses from different animal origins, they
565 become gene reservoirs with the potential to facilitate reassortments and the emergence of
566 pandemic viruses. Therefore, traditional farming systems mixing free range poultry and pigs in
567 the same backyard close to human populations presents a risk for the emergence of new
568 reassortants of influenza virus able to spread within human populations as pandemic viruses.

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

582 In that sense, several points discussed in this article may be considered to tackle epizootic
583 diseases and zoonotic diseases. This starts with a required knowledge on the ecology of
584 pathogens of interest (environmental niches, hosts, reservoirs and vectors), which may be
585 complex for multi-host pathogens. While reliable and efficient tools for pathogen monitoring are
586 usually rapidly available, complex pathogen transmission routes are often poorly characterized.
587 New technologies for the monitoring animal contact data, including social networks give now
588 access to this knowledge. Network modeling should help understanding transmission dynamics
589 in wild animal and livestock populations, which is needed to predict and reduce pathogen
590 transmission (Craft, 2015). Adapting livestock management according to ecological principles is
591 also an important avenue to improve animal health. By reducing contacts, low density farming
592 has been shown to limit pathogen transmission (Tendencia et al., 2011). Introducing genetic
593 diversity in livestock should also be considered as a sustainable way to reduce disease spread.
594 Indeed, genetically homogenous populations (monocultures) are more vulnerable to infection
595 than genetically diverse populations, which have the potential to buffer populations against

596 epidemics in nature (King and Lively, 2012; Ekroth et al., 2019). Finally, new avenues remain to
597 be explored to increase the adaptability of farmed animals. If selective breeding (artificial
598 selection) remains largely used in animal farming, recent studies have shown that new
599 prophylaxes that increase animal adaptability can be envisioned to confer resistant phenotypes
600 to otherwise susceptible animals without affecting the genetic diversity of the livestock. Indeed,
601 several invertebrates (e.g. oysters, shrimp, honey bees) can be protected from pathogen
602 infections by immune priming, which confers the potential to control infections and limit
603 pathogen transmission, even in species that cannot be vaccinated (Lafont M. et al., 2017). A high
604 interest is currently paid to immune priming, which has proven to be trans-generational in a
605 series of cultured invertebrate species (Tetreau et al., 2019). However, the epidemiological
606 consequences of trans-generational immune priming and its impact on the evolution of
607 parasite/pathogen virulence are still debated (Tidbury et al., 2012) and remain to be studied.

608

609 THE ROLE OF ANIMALS IN THE NUTRIENT CYCLES IN TERRESTRIAL AND AQUATIC 610 AGROECOSYSTEMS

611 Pushed by a dynamic political agenda on climate change, the roles of animals on biogeochemical
612 cycles, the livestock sector contribution to global anthropogenic GHG emissions (14,5% of CO₂,
613 CH₄ and N₂O emission) and mitigation options were highlighted (Gerber et al., 2013). This
614 incited animal production research to collaborate with environment science. Initial studies were
615 restricted to closed farm systems and animals were seen as “*a system*” emitting nutrients and
616 gases in the atmosphere. Moreover, some effort was given to modelling nutrient emissions
617 associated to waste management (Génermont et al., 1997), proposing some treatment options
618 (Martinez et al., 2009) and practices (Thu et al., 2012).

619 However, this first era of research focussed on partial and segmented analysis of systems,
620 neglecting more complex sets of interactions and flows between ecosystem compartments (not
621 only exchanges with the atmosphere). Research somehow neglected the role of wild and farmed

622 animals in contributing to nutrient and carbon recycling to other compartments of the
623 ecosystem like soil or crops, i.e. considering “*animals in their systems*”, and yet there are clear
624 examples. In Australia, changing dung resources thanks to import of bovine animals, has altered
625 the provision of ecosystem services by local population of dung beetles, highlighting again the
626 fact that ecological processes have to be studied in an holistic manner (Nichols et al., 2008). This
627 case study provides evidence of the importance of considering interactions between wild and
628 farmed animals and the need for collaboration, in this case between beetle ecologists and animal
629 scientists.

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

639 In the terrestrial production context, research is now addressing animal effects on nutrient and
640 carbon cycles in diverse agroecosystems. There are studies of the influence of specific
641 management factors (e.g. ruminant grazing intensity) on nutrient recycling pathways, soil
642 compaction and carbon stocks (de Faccio et al., 2010). In systems research on carbon balance,
643 the use of pasture as the main source of feed was shown to be a non-negligible carbon sink
644 under both semi-arid (e.g. Sahel) and humid environments (e.g. Amazonia) Some authors have
645 addressed the importance of developing an ecosystem approach to better assess the real
646 contribution of livestock (Assouma et al., 2017; Stahl et al., 2016) . Enteritic methane from
647 ruminants, emission from manure deposition, emission by termites, and savannah fire have been
648 accounted for as well as carbon sink function of soils and perennial ligneous vegetation in an

649 annual cycle. The carbon balance was ultimately found to be slightly negative, i.e. emissions due
650 to livestock activities are compensated by carbon sequestration in soil and trees at landscape
651 level. Thus, when environmental impact assessments integrate all the compartments of the agro-
652 ecosystem (biomass, soil, plants and animals in relation to the atmosphere), and both emission
653 and sequestration, the results contrast with partial analysis that classed African pastoral
654 ecosystems as high GHG contributors. Finally, recent work showed that the use of various
655 metrics would slightly change the evaluated impact of ruminant's methane emission on global
656 warming (Allen et al., 2018). These results, largely to do with a better understanding of GHG
657 physics, come from another community and they also stress the need to include other disciplines
658 i.e. climate and atmospheric science for evaluating environmental impact of animals GHG
659 emissions on global warming.

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

671 Such research needs continuity on the long term and design of new models (Lamprianidou et al.,
672 2015). In particular, study of factors influencing reduction efficiency (seaweed species, capacity
673 to uptake beyond physiological requirements, characteristics of production system and the
674 environment, etc.) requires an interdisciplinary research approach (Troell et al., 2003).
675 Similarly, increasing biomass recycling in terrestrial systems, or increasing carbon sequestration

676 by soils and crops, is a long run and complex effort that argues for more global scientific
677 collaboration.

678 **Conclusions**

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

688 This ambition requires interdisciplinary research: we need a new era of translational research
689 before application of results. Animal ecology has particular strengths in the study of interactions
690 between species, biodiversity, adaptive evolution in natural populations and ecosystem
691 resilience but in-situ experiments considering broader system impacts are relatively rare.
692 Animal production science has disciplinary strengths in selective breeding, production chains,
693 economics and management. It also has a heritage of methods for combining these at farm- or
694 regional systems levels. Therefore, the two disciplines have many complementary skills but a
695 stronger synergy is lacking due to old habits, i.e. perceived differences in viewpoints on the goal
696 of each discipline, different knowledge and scientific vocabulary (e.g. in quantitative genetics),
697 and different policy masters. Nevertheless, there are substantial advantages to be gained for
698 animal-related research and for society's interaction with animals, from an enhanced cross-
699 fertilization between disciplines.

700 Modelling approaches have the power to integrate disciplinary visions and knowledge and to
701 translate them into actionable research. However, so far, research has not reached the level of
702 operability required to fully "pilot" animal systems and agroecosystems. Further,

703 implementation often involves socio-economic factors and innovation processes, which hampers
704 the adoption of any proposed changes. Integration of knowledge holders from the society in the
705 process of research is also needed to tackle anticipated challenges at the interface between
706 science, policy and society. This needs the development of knowledge integration techniques
707 and enhanced collective expertise backed by participatory modelling and science. Such a process
708 begins by breaking down the disciplinary boundaries and promoting cross-fertilization between
709 the animal ecology and animal production science disciplines. This should be accompanied by
710 scientific vision, programs and policy tools that reverse the fragmentation of animal research
711 across other themes, and instead create critical mass for animal science. The analogy to the
712 emergence of One Health seems highly relevant, it is time for One Animal Research Kinship,
713 OneARK!!

714

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References

Allen, MR, Shine, KP, Fuglestvedt, JS, Millar, RJ, Cain, M, Frame, DJ, & Macey, AH: A solution to
the misrepresentations of CO₂-equivalent emissions of shortlived climate pollutants under
ambitious mitigation. *npj Climate and Atmospheric Science*, 1(1), 16.

doi.org/10.1038/s41612-018-0026-8 (2018).

Allison, G. (2004). The Influence of Species Diversity and Stress Intensity on Community
Resistance and Resilience. *Ecological Monographs* **74**, 117-134. doi: 10.1890/02-0681

[Anses \(2017\) https://www.anses.fr/fr/content/point-sur-le-virus-%C3%A9mergent-d%E2%80%99influenza-aviaire-h5n8](https://www.anses.fr/fr/content/point-sur-le-virus-%C3%A9mergent-d%E2%80%99influenza-aviaire-h5n8)

- Assouma M.H., Serça D., Guérin F., Blanfort V., Lecomte P., Touré I., ... Vayssières J. (2017). Livestock induces strong spatial heterogeneity of soil CO₂, N₂O and CH₄ emissions within a semi-arid sylvo-pastoral landscape in West Africa, *Journal of Arid Land*, 9 (2), 210-221, doi: 10.1007/s40333-017-0001-y
- Awiti, A.O. (2011). Biological Diversity and Resilience: Lessons from the Recovery of Cichlid Species in Lake Victoria. *Ecology and Society*, **16**, 9.
- Bach, L. & Dahllöf, I. (2012). Local contamination in relation to population genetic diversity and resilience of an arctic marine amphipod. *Aquatic Toxicology* **114/115**, 58-66. doi: 10.1016/j.aquatox.2012.02.003
- Baggini, C., Issaris, Y., Salomidi, M. & Hall-Spencer, J. (2015). Herbivore diversity improves benthic community resilience to ocean acidification. *Journal of Experimental Marine Biology and Ecology* **469**, 98-104. doi: 10.1016/j.jembe.2015.04.019
- Bellard, C., W. Thuiller, B. Leroy, P. Genovesi, M. Bakkenes, and F. Courchamp. 2013. Will climate change promote future invasions? *GLOBAL CHANGE BIOLOGY* 19:3740–3748. doi:10.1111/gcb.12344
- Bellard, C., Cassey, P. & Blackburn, T. M. (2016). Alien species as a driver of recent extinctions. *Biology Letters*. **12**, 20150623. doi: 10.1098/rsbl.2015.0623.
- Bellwood, D.R., Hoey, A.S. & Choat, J.H. (2003). Limited functional redundancy in high diversity systems: resilience and ecosystem function on coral reefs. *Ecology Letters* **6**, 281-285. doi: 10.1046/j.1461-0248.2003.00432.x
- Berghof, T.V.L., Poppe, M. and Mulder, H.A. 2019. Opportunities to improve resilience in animal breeding programs. *Front. Genet.* 9:692. doi: 10.3389/fgene.2018.00692
- Betts M.G., Wolf C., Ripple W.J., Phalan B., Millers K.A., Duarte A.,... Levi T. (2017). Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* 547: 441-444
- Boissier, J., Grech-Angelini, S., Webster, B.L., Allienne, J.F., Huyse, T., Mas-Coma, S., ... Mittermeier, G. (2016). Outbreak of urogenital schistosomiasis in Corsica (France): an epidemiological case study. *Lancet Infect Dis.* 16(8):971-9. doi: 10.1016/S1473-3099(16)00175-4

- Borchers, M.R., Chang, Y.M., Tsai, I.C., Wadsworth, B.A. & Bewley, J.M. (2016). A validation of technologies monitoring dairy cow feeding, ruminating, and lying behaviors. *Journal of Dairy Science* 99, 7458-7466.
- Bregman, T.P., Lees, A.C., MacGregor, H.E.A., Darski, B., de Moura, N.G., Aleixo, A., ... Tobias, J.A. (2017). Using avian functional traits to assess the impact of land-cover change on ecosystem processes linked to resilience in tropical forests. *Proceedings of the Royal Society - B* **283**, 20161289. doi: 10.1098/rspb.2016.1289
- Carlisle, L. (2014). Diversity, flexibility, and the resilience effect: lessons from a social ecological case study of diversified farming in the northern Great Plains, USA. *Ecology and Society* **19**, 45. doi: 10.5751/ES-06736-190345
- Craft, M. E. (2015) Infectious disease transmission and contact networks in wildlife and livestock, *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**, 1669. doi: 10.1098/rstb.2014.0107.
- Chevin, L.M. & Beckerman, A.P. (2011). From adaptation to molecular evolution. *Heredity* **108**, 457-459. doi:10.1038/hdy.2011.96
- Chomba C. & Nyirenda V. (2014). Game Ranching: A Sustainable Land Use Option and Economic Incentive for Biodiversity Conservation in Zambia, *Open Journal of Ecology*, 4 (9), 571-581. doi:10.4236/oje.2014.49047
- Clavel, J., R. Julliard, & V. Devictor. (2011). Worldwide decline of specialist species: toward a global functional homogenization? *Frontiers in Ecology and the Environment* 9, 222-228. doi:10.1890/080216
- Danchin-Burge C., Leroy G., Brochard M., Moureaux S., & Verrier E. (2012) Evolution of the genetic variability of eight French dairy cattle breeds assessed by pedigree analysis. *J. Anim. Breed. Genet.* 129, 206-217.
- Darwin, C. (1859) *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.*
- de Faccio Carvalho P.C., Anghinoni I., De Moraes A., De Souza E.D., Sulc R.M., Lang C.R., ... Bayer

- C. (2010). Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems, *Nutrient Cycling in Agroecosystems*, 88 (2), 259-273, doi: 10.1007/s10705-010-9360-x,
- de Juan, S., Thrush, S.F. & Hewitt, J.E. (2013). Counting on β -diversity to safeguard the resilience of estuaries. *PLoS ONE* 8, e65575. doi: 10.1371/journal.pone.0065575
- Destoumieux-Garzón, D., Mavingui, P., Boetsch, G., Boissier, J., Darriet, F., Duboz, P., ... Voituren, Y. (2018). The One Health concept: 10 years old and a long road ahead. *Frontiers in Veterinary Science*. 5:14. doi: 10.3389/fvets.2018.00014
- Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M. & Tichit, M. (2013). Prospects from agroecology and industrial ecology for animal production in the 21st century. *Animal* 7 1028-1043
- Ekroth, A.K.E., Rafaluk-Mohr, C., King K.C. (2019). Host genetic diversity limits parasite success beyond agricultural systems: a meta-analysis. *Proc Biol Sci*. 286(1911): 20191811. doi: 10.1098/rspb.2019.1811
- FAO (2015) Second state of the world's animal genetic resources for food and agriculture. Rome, Italy, FAO.
- Fischer, J., Lindenmayer, D.B., & Manning, A.D. (2006). Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes. *Frontiers in Ecology and the Environment* 4, 80-86. doi: 10.1890/1540-9295(2006)004[0080:BEFART]2.0.CO;2
- Frost P.G.H. & Bond I. (2008) The CAMPFIRE programme in Zimbabwe: Payments for wildlife services, *Ecological Economics*, 65 (4), 776-787, doi:10.1016/j.ecolecon.2007.09.018
- Fuller, R. A., Irvine, K. N., Devine-Wright, P., Warren, P. H., & Gaston, K. J. (2007). Psychological benefits of greenspace increase with biodiversity. *Biology letters*, 3(4), 390-394.
- Gagic, V., Bartomeus, I., Jonsson, T., Taylor, A., Winqvist, C., Fischer, C., ... Bommarco, R. (2015). Functional identity and diversity of animals predict ecosystem functioning better than species-based indices. *Proceedings of the Royal Society B: Biological Sciences*, 282(1801),

20142620–20142620. doi:10.1098/rspb.2014.2620

Génermont, S. & Cellier, P. (1997). A mechanistic model for estimating ammonia volatilization from slurry applied to bare soil, *Agricultural and Forest Meteorology*, 88 (1), 145-167, doi:10.1016/S0168-1923(97)00044-0

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., ... Tempio, G. (2013). Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Gladstone-Gallagher, R.V., Pilditch, C.A., Stephenson, F. & Thrush S.F. (2019). Linking traits across ecological scales determines functional resilience. *Trends in Ecology & Evolution*, in press, doi.org/10.1016/j.tree.2019.07.010

Gleiss, A.C., Wilson, R.P., & Shepard, E.L. (2011). Making overall dynamic body acceleration work: on the theory of acceleration as a proxy for energy expenditure. *Methods in Ecology and Evolution*, 2(1), 23-33.

Gould, S.J. & Lloyd, E.A. (1999) Individuality and adaptation across levels of selection: how shall we name and generalize the unit of Darwinism? *Proceedings of the National Academy of Sciences* **96**, 11904-11909.

Grant, P.R., Grant, B.R., Huey, R.B., Johnson, M.T J., Knoll, A.H., Schmitt, J., & Grant, P.R. (2017). Evolution caused by extreme events. . *Philosophical Transactions of the Royal Society B: Biological Sciences* 372: 20160146.

Greenfield, B.L., Kraan, C., Pilditch, C.A. & Thrush, S.F. (2016). Mapping functional groups can provide insight into ecosystem functioning and potential resilience of intertidal sandflats. *Marine Ecology Progress Series* **548**, 1-10. doi: 10.3354/meps11692

Headon D. (2013). Systems biology and livestock production. *Animal* 7: 1959-1963.

Heams T. (2009). Variation. In T. Heams, P. Huneman, G. Lecointre, M. Silberstein (Eds), *Les Mondes darwiniens*, Editions Syllepse, 17-30.

Højsgaard, S. & Friggens, N.C. (2010). Quantifying degree of mastitis from common trends in a

- panel of indicators for mastitis in dairy cows. *Journal of Dairy Science* 93, 582-592
- Holling, C.S. (1996) Engineering resilience versus ecological resilience. In: *Engineering within ecological constraints*, pp. 31–44. National Academy Press, Washington, DC.
- Hufbauer, R. A. et al. 2012. Anthropogenically induced adaptation to invade (AIAI): contemporary adaptation to human-altered habitats within the native range can promote invasions. - *Evol. Appl.* 5: 89–101.
- Jenouvrier, S., Péron C., & Weimerskirch H. (2015). Extreme climate events and individual heterogeneity shape life- history traits and population dynamics. *Ecological Monographs* 85:605–624.
- Jones B.T.B., Diggle R.W., & Thouless, C. (2015). From Exploitation to Ownership: Wildlife-Based Tourism and Communal Area Conservancies in Namibia, In: *Institutional Arrangements for Conservation, Development and Tourism in Eastern and Southern Africa*, (R. Van Der Duim, M. Lamers, J. Van Wijk, eds.), Springer Netherlands, Dordrecht, 17-37, doi: 10.1007/978-94-017-9529-6_2
- Kaarlejärvi, E., Hoset, K.S. & Olofsson, J. (2015). Mammalian herbivores confer resilience of Arctic shrub-dominated ecosystems to changing climate. *Global Change Biology* 21, 3379-3388. doi: 10.1111/gcb.12970
- Kaiser-Bunbury, C.N., Mougai, J., Whittington, A.E., Valentin, T., Gabriel, R., Olesen, J.M. & Blüthgen, N. (2017). Ecosystem restoration strengthens pollination network resilience and function. *Nature* 542, 223-229. doi: 10.1038/nature21071
- Kammili, T., Hubert, B. & Tourrand, J.F. (2011). A paradigm shift in livestock management: from resource sufficiency to functional integrity, 28th - 29th June 2008, Hohhot, China. Morières: Ed. de la Cardère, 270 p. Workshop on A paradigm shift in livestock management, 2008-06-28/2008-06-29, Hohhot (Chine).
- Kaplan, B.S., Torchetti, M.K., Lager, K.M., Webby, R.J., & Vincent AL. (2017). Absence of clinical disease and contact transmission of North American clade 2.3.4.4 H5NX HPAI in experimentally infected pigs. *Influenza Other Respir Viruses*. doi:10.1111/irv.12463.

- Keating, B.A., Carberry, P.S., Bindraban, P.S., Asseng, S., Meinke, H. & Dixon, J. (2010). Eco-efficient agriculture: concepts, challenges, and opportunities. *Crop Science*. 50 S109-2119.
- Keesing, F., Belden, L. K., Daszak, P., Dobson, A., Harvell, C. D., Holt, R. D., ... Ostfeld, R. S. (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*, 468(7324), 647–652. [doi:10.1038/nature09575](https://doi.org/10.1038/nature09575)
- King, K. C. and Lively, C. M. (2012) Does genetic diversity limit disease spread in natural host populations, *Heredity*. **109**(4), 199–203. doi: 10.1038/hdy.2012.33.
- Kühnel, S. & Blüthgen, N. (2015). High diversity stabilizes the thermal resilience of pollinator communities in intensively managed grasslands. *Nature Communications* **6**, 7989. doi : 10.1038/ncomms8989
- Kuijper, D. P. J., Churski, M., Trouwborst, A., Heurich, M., Smit, C., Kerley, G. I. H., & Cromsigt, J. P. G. M. (2019). Keep the wolf from the door: How to conserve wolves in Europe's human-dominated landscapes?. *Biological Conservation*, 235, 102-111.
- Lafont, M, Petton, B, Vergnes, A, Pauletto, M, Segarra, A, Gourbal, B, Montagnani, C. (2017). Long-lasting antiviral innate immune priming in the Lophotrochozoan Pacific Oyster *Crassostrea gigas*. *Sci Rep*. **7**(1):13143. doi:10.1038/s41598-017-13564-0.
- Lamprianidou F., Telfer T., & Ross L.G. (2015). A model for optimization of the productivity and bioremediation efficiency of marine integrated multitrophic aquaculture, *Estuarine, Coastal and Shelf Science*, 164(C), 253-264, doi:10.1016/j.ecss.2015.07.045
- Lande, R. & Arnold, S. J. (1983) The measurement of selection on correlated characters. *Evolution* 37:1210–1226.
- Lindgren, M., Checkley, D.M. Jr, Ohman, M.D., Koslow, J.A. & Goericke, R. (2016). Resilience and stability of a pelagic marine ecosystem. *Proceedings of the Royal Society - B* **283**, 20151931. doi: 10.1098/rspb.2015.1931
- López, D.R., Brizuela, M.A., Willems, P., Aguiar, M.R., Siffredi, G. & Bran, D. (2013). Linking ecosystem resistance, resilience, and stability in steppes of North Patagonia. *Ecological Indicators* **24**, 1-11. doi: 10.1016/j.ecolind.2012.05.014

- Lycett, S.J., Bodewes, R., Pohlmann, A., Banks, J., Bányai, C., Boni, M.J., ... Kuiken, T. (2016) Role for migratory wild birds in the global spread of avian influenza H5N8. The Global Consortium for H5N8 and Related Influenza Viruses. *Science*. 354:6309
- Mackenzie, J.S., & Jeggo, M. (2013). Reservoirs and vectors of emerging viruses. *Curr Opin Virol*. 3(2):170-9. doi: 10.1016/j.coviro.2013.02.002
- Martin, J.-L. et al. 2016. The need to respect nature and its limits challenges society and conservation science. - Proc. Natl. Acad. Sci. U. S. A. 113: 6105–12
- Martinez, J., Dabert, P., Barrington, S., & Burton, C. (2009). Livestock waste treatment systems for environmental quality, food safety, and sustainability, *Bioresource technology*, 100 (22), 5527-5536, doi:10.1016/j.biortech.2009.02.038
- Maxwell, S.L., Fuller, R.A., Brooks, T.M., & Watson, J.E.M. (2016). The ravages of guns, nets and bulldozers. *Nature* 536: 143-145.
- McCauley, D. (2008). "Sustainable development and the 'governance challenge': the French experience with Natura 2000." *European Environment* 18(3): 152-167.
doi.org/10.1002/eet.478
- McKechnie, A.E., & Wolf, B.O. (2010). Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. *Biology Letters* 6:253–6.
- Messier C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., Mina, M., Aquilué, N., Fortin, M.J., & Puettmann, K. 2019. The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, 6-21, doi.org/10.1186/s40663-019-0166-2
- Mijatović, D., Van Oudenhoven, F., Eyzaguirre, P., & Hodgkin, T. (2013). The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. *International Journal of Agricultural Sustainability* **11**, 95-107. doi: 10.1080/14735903.2012.691221
- Milhazes-Cunha H., Otero A. (2017) Valorisation of aquaculture effluents with microalgae: The Integrated Multi-Trophic Aquaculture concept, *Algal Research*, 24 (Part B), 416-424, DOI:

doi:10.1016/j.algal.2016.12.011

Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B., & Worm, B. (2011). How many species are there on earth and in the ocean? *PLoS Biology*, 9(8), 1–8.

doi:10.1371/journal.pbio.1001127

Morán-Ordóñez, A., R. Bugter, et al. (2013). "Temporal Changes in Socio-Ecological Systems and Their Impact on Ecosystem Services at Different Governance Scales: A Case Study of Heathlands." *Ecosystems* 16(5): 765-782. doi.org/10.1007/s10021-013-9649-0

Morand S., McIntyre K.M. & Baylis M. (2014). Domesticated animals and human infectious diseases of zoonotic origins: Domestication time matters. *Infection, Genetics and Evolution*. 24:76-81. doi: 10.1016/j.meegid.2014.02.013

Moretti, M., Duelli, P., & Obrist, M.K. (2006). Biodiversity and resilience of arthropod communities after fire disturbance in temperate forests. *Oecologia* **149**, 312-327. doi: 10.1007/s00442-006-0450-z

Mori, A.S., Furukawa, T. & Sasaki, T. (2013). Response diversity determines the resilience of ecosystems to environmental change. *Biological Reviews* **88**, 349-364. doi: 10.1111/brv.12004

Morrissey, M.B., Kruuk, L.E.B., & Wilson. A.J. (2010). The danger of applying the breeder's equation in observational studies of natural populations. *Journal of Evolutionary Biology* 23:2277–2288.

Mouysset, L., Doyen L., & Jiguet F. (2013). From Population Viability Analysis to Coviability. *Conservation Biology* 28:187–201.

Nichols, E., S. Spector, et al. (2008). "Ecological functions and ecosystem services provided by Scarabaeinae dung beetles." *Biological Conservation* 141(6): 1461-1474.

doi.org/10.1016/j.biocon.2008.04.011

[OIE \(2016\)](#)

http://www.oie.int/wahis_2/public/wahid.php/Reviewreport/Review?page_refer=MapFnullEventReport&reportid=20335

- Oliver, T.H., Heard, M.S., Isaac, N.J.B., Roy, D.B., Procter, D., Eigenbrod, F., ... Bullock, J.M. (2015) Biodiversity and resilience of ecosystem functions. *Trends in Ecology & Evolution* **30**, 673-684. doi: 10.1016/j.tree.2015.08.009
- Oliver, T.H., Heard, M.S., Isaac, N.J.B., Roy, D.B., Procter, D., Eigenbrod, F., ... Bullock, J.M. (2016). A synthesis is emerging between biodiversity-ecosystem function and ecological resilience research: Reply to Mori. *Trends in Ecology & Evolution* **31**, 89-92. doi: 10.1016/bs.aecr.2015.09.004
- Oliver, T.H., Isaac, N.J.B., August, T.A., Woodcock, B.A., Roy, D.B. & Bullock, J.M. (2015). Declining resilience of ecosystem functions under biodiversity loss. *Nature Communications* **6**, 10122. doi: 10.1038/ncomms10122
- Oltenacu, P. A. & D. M. Broom (2010). The impact of genetic selection for increased milk yield on the welfare of dairy cows. *Animal Welfare* 19:39–49.
- Ostrom E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems, *Science*, 325:24
- Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P. and Thomas, M. B. (2016). Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences of the United States of America*. **113**, 7575–7579. doi: 10.1073/pnas.1602205113.
- Palumbi, S.R. (2001). Humans as the World's Greatest Evolutionary Force. *Science* 293:1786–1790.
- Pauly, D., Christensen, V., Guenette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J., ... Zeller, D. (2002). Towards sustainability in world fisheries. *Nature* **418**, 689-695. doi: 10.1038/nature01017
- Pearce-Duvet, J.M. (2006). The origin of human pathogens: evaluating the role of agriculture and domestic animals in the evolution of human disease. *Biol Rev Camb Philos Soc*. 81(3):369-82.
- Petchey, O.L. & Gaston, K.J. (2006). Functional diversity: back to basics and looking forward. *Ecology Letters* **9**, 741-758. doi: 10.1111/j.1461-0248.2006.00924.x

Prunet, P., Overli, O., Douxfils, J., Bernardini, G., Kestemont, P., & Baron, D. (2012). Fish welfare and genomics. *Fish Physiology and Biochemistry* 38(1): 43-60.10.

Puillet, L., Réale, D., & Friggens N.C. (2016). Disentangling the relative roles of resource acquisition and allocation on animal feed efficiency: Insights from a dairy cow model. *Genetics Selection Evolution* 48:1-16.

Raymond, B., Lea, M.A., Patterson, T., Andrews-Goff, V., Sharples, R., Charrassin, J.B., ... Hindell, M.A. (2015) Important marine habitat off east Antarctica revealed by two decades of multi-species predator tracking. *Ecography* 38, 121-129. doi: 10.1111/ecog.01021

Rey, O., Danchin, E., Mirouze, M., Loot, C. & Blanchet, S. (2016). Adaptation to Global Change: A Transposable Element–Epigenetics Perspective. *Trends in Ecology & Evolution* 31, 514-526. doi:10.1016/j.tree.2016.03.013

Rezza, G., Nicoletti, L., Angelini, R., Romi, R., Finarelli, A.C., Panning, M., ... Cassone, A., for the CHIKV study group (2007). Infection with chikungunya virus in Italy: an outbreak in a temperate region. *The Lancet*, 370(9602):1840-1846

Ripperger, S., Josic, D., Hierold, M., Koelpin, A., Weigel R., Hartmann M., ... Mayer F. (2016). Automated proximity sensing in small vertebrates: design of miniaturized sensor nodes and first field tests in bats. *Ecol Evol.* 6(7):2179-89

Sabatier, R., Doyen, L. and Tichit, M. (2014). Heterogeneity and the trade-off between ecological and productive functions of agro-landscapes: A model of cattle-bird interactions in a grassland agroecosystem. *Agric Systems.* 126: 38-49

Sadoul, B., Evoung Mengues, P., Friggens, N.C., Prunet, P. & Colson, V. (2014). A new method for measuring group behaviours of fish shoals from recorded videos taken in near aquaculture conditions. *Aquaculture* 430, 179-187.

Sarrazin, F., and J. Lecomte. 2016. Evolution in the Anthropocene. *Science* 351:922–923.

Sasaki, T., Furukawa, T., Iwasaki, Y., Seto, M. & Mori, A.S. (2015) Perspectives for ecosystem management based on ecosystem resilience and ecological thresholds against multiple and stochastic disturbances. *Ecological Indicators* 57, 395-408. doi:

10.1016/j.ecolind.2015.05.019

Schippers, P., van der Heide, C.M., Koelewijn, H.P., Schouten, M.A.H., Smulders, R.M.J.M., Cobben, M.M.P., ... Verboom, J. (2015). Landscape diversity enhances the resilience of populations, ecosystems and local economy in rural areas. *Landscape Ecology* **30**, 193-202. doi:

10.1007/s10980-014-0136-6

Schlaepfer, M.A., Runge, M.C., & Sherman, P.W. (2002). Ecological and evolutionary traps. *Trends in Ecology & Evolution* **17**:474–480.

Sherf, B. (2000). World watch list for domestic animal diversity, 3rd edition. FAO, Rome.

Siepielski, A.M., Gotanda K.M., Morrissey M.B., Diamond S.E., DiBattista J.D., & Carlson S.M.

(2013). The spatial patterns of directional phenotypic selection. *Ecology Letters* **16**:1382–1392.

Siepielski, A.M., Morrissey, M.B., Buoro, M., Carlson S.M., Caruso, C.M., Clegg, S.M., Coulson, T., Dibattista, J., Gotanda, K. M., Francis, C. D., Hereford, J., Kingsolver, J. G., Sletvold, N., Svensson, E. I., Wade, M. J. and Maccoll, A.D.C. (2017). Precipitation drives global variation in natural selection. *Science* **355**:959–962.

Soteriades, A.D., Stott, A.W., Moreau, S., Charroin, T., Blanchard, M., Liu, J. & Faverdin, P. (2016). The relationship of dairy farm eco-efficiency with intensification and self-sufficiency. Evidence from the French dairy sector using life cycle analysis, data envelopment analysis and partial least squares structural equation modelling. *PLoS ONE* **11** e0166445

Stahl, C., Fontaine, S., Klumpp, K., Picon-Cochard, C., Grise, M.M., Dezécache, C., ... Blanfort V. (2017). Continuous soil carbon storage of old permanent pastures in Amazonia, *Global Change Biology*, **23** (8), 3382-3392, doi: 10.1111/gcb.13573

Stearns, S.C. (1977) The evolution of life history traits: A Critique of the Theory and a Review of the Data. *Annual Review of Ecology, Evolution, and Systematics* **8**:145–171.

Tabacchi, E., Steiger, J., Corenblit, D., Monaghan, M.T. & Planty-Tabacchi, A.-M. (2009).

Implications of biological and physical diversity for resilience and resistance patterns within highly dynamic river systems. *Aquatic Sciences* **71**, 279-289. doi: 10.1007/s00027-

009-9195-1

- Tendencia E.A., BosmabJohan, R.H., Verreth A.J. (2011) White spot syndrome virus (WSSV) risk factors associated with shrimp farming practices in polyculture and monoculture farms in the Philippines. *Aquaculture*. **311(1-4)**, 87-93
- Tetreau, G., Dhinaut, J., Gourbal, B., Moret, Y. Trans-generational Immune Priming in Invertebrates: Current Knowledge and Future Prospects. *Front Immunol*. 10,1938. doi: 10.3389/fimmu.2019.01938.
- Thien Thu, C.T., Cuong, P.H., Hang, L.T., Chao, N.V., Anh, L.X., Trach, N.X., & Sommer, S.G. (2012). Manure management practices on biogas and non-biogas pig farms in developing countries – using livestock farms in Vietnam as an example, *Journal of cleaner production*, 27(C), 64-71, doi: 10.1016/j.jclepro.2012.01.006
- Tidbury, H.J., Best, A., Boots, M. (2012) The epidemiological consequences of immune priming. *Proc Biol Sci*. **279**(1746),4505-12. doi: 10.1098/rspb.2012.1841
- Tixier-Boichard, M., Verrier, E., Rognonn X., & Zerjaln T. (2015). Farm animal genetic and genomic resources from an agroecological perspective. *Frontiers in Genetics* 6, 153.
- Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A.H., Kautsky, N., & Yarish, C. (2003). Integrated mariculture: asking the right questions, *Aquaculture*, 226 (1), 69-90, doi:10.1016/S0044-8486(03)00469-1
- Ummenhofer, C.C. & Meehl, G.A. (2017). Extreme weather and climate events with ecological relevance: a review. *Phil. Trans. R. Soc. B* 372:20160135.
- Valcu, C.M. & Kempnaers, B. (2014). Proteomics in behavioral ecology. *Behavioral Ecology* **26**, 1-15. doi:10.1093/beheco/aru096
- van Gils, J.A., Lisovski, S., Lok, T., Meissner, W., Ozarowska, A., de Fouw, J., ... Klaassen, M. (2016). Body shrinkage due to Arctic warming reduces red knot fitness in tropical wintering range. *Science* 352:819–821.
- Vayssières, J., Guerrin, F., Paillat, J.-M., & Lecomte, P. (2009). GAMEDE: A global activity model for evaluating the sustainability of dairy enterprises. Part I – Whole-farm dynamic model.

Villars, C., Bergouignan, A., Dugas, J., Antoun, E., Schoeller, D. A., Roth, H., ... Simon, C. (2012).

Validity of combining heart rate and uniaxial acceleration to measure free-living physical activity energy expenditure in young men. *Journal of applied physiology*, 113(11), 1763-1771.

Visser, M.E., Noordwijk, A.J.V., Tinbergen, J.M., & Lessells, C.M. (1998). Warmer springs lead to

mistimed reproduction in great tits (*Parus major*). *Proceedings of the Royal Society B: Biological Sciences* 265:1867–1870.

Wathes, C.M, Kristensen, H.H., Aerts, J.M. & Berckmans, D. (2008). Is precision livestock farming

an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? *Computers and Electronics in Agriculture* 64, 2-10.

Woolhouse, M.E.J., Haydon, D.T. & Antia, R. (2005). Emerging pathogens: the epidemiology and

evolution of species jumps. *Trends in Ecol. Evol.* 20, 238-244. doi:

10.1016/j.tree.2005.02.009