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► To cite this version:

Vanesse Labeyrie, Martine Antona, Jacques Baudry, Didier Bazile, Örjan Bodin, et al.. Networking agrobiodiversity management to foster biodiversity-based agriculture. A review. *Agronomy for Sustainable Development*, 2021, 41 (1), 10.1007/s13593-020-00662-z . hal-03410833

HAL Id: hal-03410833

<https://hal.science/hal-03410833>

Submitted on 2 Nov 2021

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1 **Title: Networking agrobiodiversity management to foster biodiversity-based agriculture. A review**

2

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24 **Abstract**

25 Biodiversity-based agriculture is the main form of agriculture practiced by smallholder farmers, who
26 produce half the world's food, especially in the Global South. This form of agriculture relies on planned
27 biodiversity intentionally managed by farmers and on the associated biodiversity that spontaneously
28 colonizes the agroecosystem. In recent decades, there have been increasing calls from researchers and
29 society to support biodiversity-based agriculture as an alternative paradigm to today's industrial
30 agriculture. Building adapted governance and management systems for enhancing farmers' access to
31 agrobiodiversity is a key challenge for the development of biodiversity-based agriculture. To achieve
32 this, a better understanding of how farmer's access agrobiodiversity is needed, and in particular, how
33 this access is affected by interactions between farmers and with institutions, i.e. social networks.

34 In this article, we first review the literature on the role of social networks in farmers' access to
35 agrobiodiversity, in the form of crop diversity and associated biodiversity, and the related knowledge to
36 manage this diversity. This review points at a major knowledge gap concerning how the composition
37 and structure of these networks affect farmers' access to agrobiodiversity. Then, we review literature on
38 social-ecological networks to identify how this framework developed for environmental management
39 could contribute in getting a better understanding of the role of social networks' structure and
40 composition in farmers' access to agrobiodiversity. Based on this review, we propose a social-ecological
41 network framework dedicated to crop diversity. Finally, we present potential applications of this
42 framework to develop new participatory approaches for agrobiodiversity management and governance,
43 adapted to biodiversity-based agriculture.

44

45 **Keywords**

46 Agrobiodiversity, agroecology, social networks, social-ecological interactions, participatory
47 approaches, management/governance

48	Content
49	1. Introduction
50	
51	2. Social networks and farms' access to agrobiodiversity
52	2.1. Knowledge circulation networks and social learning
53	2.2. Collaboration networks and access to associated biodiversity
54	2.3. Seed circulation networks and access to crop diversity
55	
56	3. Linking the structure and outcomes of agrobiodiversity management networks: A social-ecological
57	framework
58	3.1. Insights from social-ecological networks research on crop diversity access
59	3.2. A social-ecological network framework for crop diversity management
60	
61	4. Conclusion and perspectives
62	5. Acknowledgements
63	6. Declarations
64	7. References
65	
66	
67	

68 1. Introduction

69 Biodiversity-based farming is the main form of agriculture practiced by smallholder farmers, who
70 represent about 85 % of all farms in the world (Lowder et al. 2016) and produce an estimated 50% of
71 the food calories at the global scale (Ricciardi et al. 2018). A fast-growing literature provides evidence
72 for the role of biodiversity in supporting ecosystem services provision in agroecosystems and in
73 enhancing their resilience (Dainese et al. 2019; Renard and Tilman 2019, Roux et al. 2009). It pleads
74 also for supporting biodiversity-based agriculture as an alternative development paradigm (Frison 2016;
75 Tscharntke et al. 2012). This form of agriculture relies on the management of agrobiodiversity, broadly
76 defined as “*the diversity of living organisms that contribute to food and agriculture*” (Qualset et al.
77 1995). It includes three components: *i*) planned agrobiodiversity, i.e. organisms that are intentionally
78 implanted and tended in farmlands, *ii*) associated agrobiodiversity, i.e. organisms that spontaneously
79 colonize the agroecosystem, such as pollinators or pest predators, and *iii*) the diversity of associated
80 knowledge systems (Jackson et al. 2012). Supporting biodiversity-based agriculture is a core challenge,
81 as recent studies suggest that agroecosystems’ homogenization increases their vulnerability to climatic,
82 biotic, or economic variability (e.g., Renard and Tilman 2019). Such a homogenization from the plot to
83 the landscape scale thus jeopardizes the resilience of agricultural and food systems in the face of global
84 changes.

85 Facilitating farmers' access to agrobiodiversity is key to support biodiversity-based agriculture
86 (Almekinders and Louwaars 2002). This cannot be achieved without developing collaborative and
87 pluralistic governance approaches (Leventon et al. 2017; Halewood, Noriega, Louafi 2013), grounded
88 in local socioeconomic dynamics, and without recognizing the diversity of values, rules and practices
89 related to the use and circulation of agrobiodiversity (Jackson et al. 2007). In the past, policies and
90 regulatory frameworks were rather designed to promote highly standardized cropping systems
91 (monocultures) and agricultural landscapes in order to access world competitive markets. The
92 implementation of these policies raised major concerns among civil society organizations and
93 researchers. Both argued that such regulatory frameworks lead to the disempowerment of small farmers
94 and to their impoverishment because they reduce the availability and increase restrictions on farms’
95 access to the biological and cognitive resources required for low-input agriculture.

96 Farmers play a key role in maintaining, generating and circulating agrobiodiversity, together with a wide
97 range of stakeholders, e.g., governmental and non-governmental organizations, the private sector, and
98 international and regional institutions (McGuire and Sperling 2016, Hauck et al. 2016). However, little
99 is known about how this diversity of stakeholders and the way they interact together determine the
100 availability of a large pool of agrobiodiversity at the landscape level, and affect the ability of individual
101 farmers to access this pool (Fig 1). This gap calls for new research on how the social relational networks
102 involving these different stakeholders favor or limit farms’ access to agrobiodiversity.



103
 104 **Figure 1. (a) Heterogeneous agricultural landscape on the margins of tropical forests in the southern**
 105 **Highlands, region of the Andringitra massif, Ambohimahasina, Madagascar (© Stéphanie Carrière,**
 106 **2012).** The diversified agricultural landscapes shaped by smallholder farmers, such as those observed in this region
 107 of Madagascar, are home to a rich associated biodiversity that includes insectivorous birds, bats, or pollinators; **b)**
 108 **Exchange of cuttings of a diversity of taro (*Colocasia esculenta*) landraces between women farmers in**
 109 **Wakatr tribe, Ouvea, New Caledonia. (© Vanesse Labeyrie, 2010).** Crop diversity is one component of
 110 agrobiodiversity playing a key role in smallholder agriculture. Farmers' access to this diversity is strongly
 111 conditioned by their social network. For instance, in New-Caledonia, one single farmer can grow dozens of taro
 112 landraces she has obtained from a variety of sources, mostly from other farmers, but also from market or extension
 113 services.

114 A substantial literature shows that the structure and composition of social networks play a crucial role
 115 in driving the management and governance outcomes for a wide range of natural resources (Barnes et
 116 al. 2016; Bodin and Crona 2009). Applying such social networks framework to the field of
 117 agrobiodiversity could help develop innovative governance systems for enhancing farmer's access to
 118 agrobiodiversity, based on the empowerment of local stakeholders and the collaboration across and
 119 within institutional levels (Folke et al. 2005).

120 The study of social networks involved in agrobiodiversity management expanded over the last decade,
 121 with a main focus on crop diversity (Calvet-Mir and Salpeteur 2016; Coomes et al. 2015; Thomas et al.
 122 2011; Pautasso et al. 2013), while a small number of studies were dedicated to associated diversity (e.g.,
 123 Hauck et al. 2016), and knowledge (e.g., Isaac et al. 2012). This literature encompasses scattered case
 124 studies using different methods, which hampers the formulation of general conclusions. In turn, this lack
 125 of knowledge hinders the development of adapted governance systems to support biodiversity-based
 126 agriculture. We argue that this could be enhanced in two ways.

127 First, there is a need to formalize a conceptual framework for improving the general understanding on
 128 how the structure and composition of the social networks linking the stakeholders involved in
 129 agrobiodiversity management affect the access of farms to this resource. We propose in this paper to fill
 130 this gap by identifying how the social-ecological network framework developed in the field of

131 environmental management (Bodin 2017) could be applied to the three components of agrobiodiversity
132 (e.g. crop biodiversity, associated diversity and knowledge). We then lay the foundations of a conceptual
133 framework dedicated to crop biodiversity, as the previous social-ecological network framework built
134 for common-pool natural resources could not be applied. Such a framework would especially be
135 instrumental in guiding the implementation of large-scale cross-sectional surveys or simulation studies,
136 required for building generic knowledge.

137 Second, there is a need to apply the results of this research to develop innovative agrobiodiversity
138 management and governance mechanisms adapted to biodiversity-based agriculture through
139 participatory approaches. Integrating these results in participatory modelling would especially allow to
140 explore how different patterns of interactions between stakeholders affect farms' access to
141 agrobiodiversity. This could help in designing more effective ways of collective and institutional
142 organization for agrobiodiversity management and governance. For instance, this approach could
143 contribute in designing modes of organizations for community-based agrobiodiversity management
144 initiatives, such as community seed banks (Vernooy, Shrestha, Sthapit 2015), experience-sharing
145 networks (Rosset et al. 2011) or landscape approaches (Vialatte et al. 2019).

146 This paper further details these two gaps, and contributes in addressing them. The first section reviews
147 the literature that explores the role of social networks in farmers' access to agrobiodiversity. The second
148 section proposes a network-centered framework for investigating this relationship, focusing on crop
149 diversity for which existing social-ecological network frameworks do not apply. Last, the third section
150 raises perspectives on applications of social network analysis to participatory modelling approaches
151 aiming at building innovative agrobiodiversity management and governance mechanisms. This paper
152 focuses on diversified agriculture, which is particularly prevalent in the Global South, but we believe
153 that its conclusions are also relevant for the transition of low-diversity agriculture.

154 **2. Social networks and farms' access to agrobiodiversity**

155 The majority of smallholder farmers in the global south practice agriculture based on the management
156 of agrobiodiversity at different scales, from the plot to the landscape, or even across landscapes (Altieri
157 et al. 2012). Growing a diversity of crop species and varieties is a widespread strategy in small-scale
158 agriculture, and farmers' varieties are genetically diverse (Jarvis et al. 2008). Furthermore, smallholder
159 farmers frequently diversify their land uses, combining different annual, perennial or agroforestry
160 cropping systems in the same landscape, and including natural and semi-natural areas such as
161 hedgerows, fallows, pastures and forests (Tscharntke et al. 2012). An abundant literature highlights the
162 importance of biodiversity at the population, community and landscape levels for the food security of
163 small farms (Thrupp 2000; Waha et al. 2018), for dietary diversity (Remans et al. 2014), and for the
164 balance between income and food production (Anderman et al. 2014). Ecological studies further stress

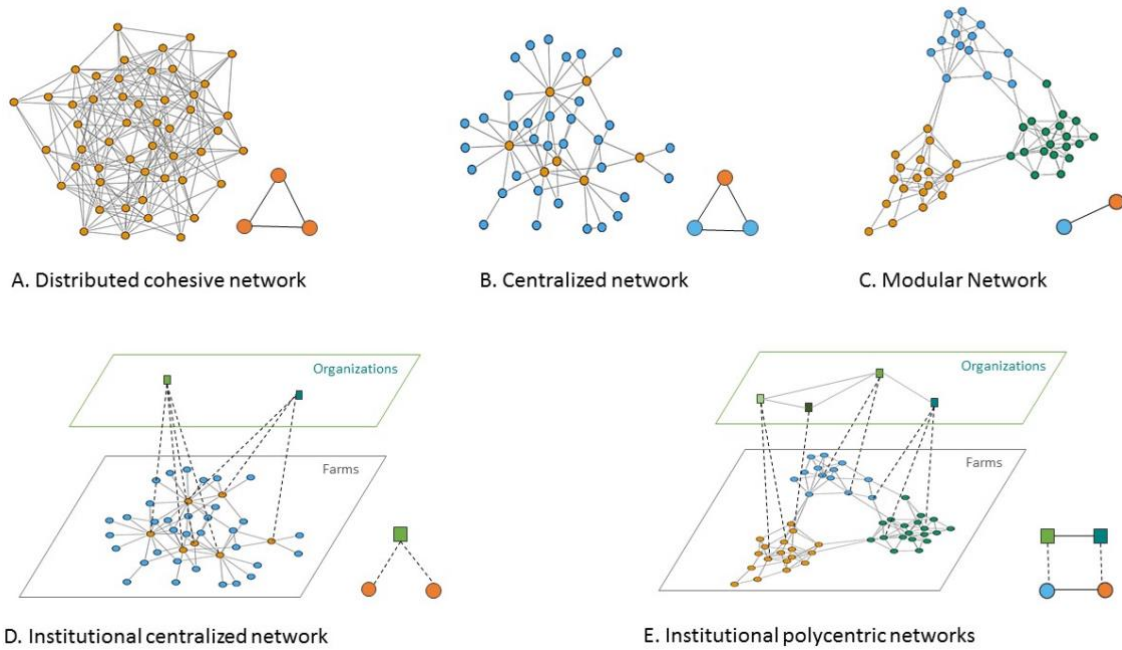
165 the effect of biodiversity on the productivity of agroecosystems at different scales in the long term, and
166 on its stability in the face of socio-economic and biological or climatic perturbations (Clough et al. 2011;
167 Lin 2011; Renard and Tilman 2019). Beyond productivity, biodiversity drives agroecosystem capacity
168 to deliver a variety of ecosystem services (DeClerck et al. 2016; Hatt et al. 2018) and stabilizes the
169 provision of these services over time (Isbell et al. 2017; Mijatović et al. 2013). Diversification of crop
170 and of land uses in particular has been shown to increase associated diversity, including that of beneficial
171 organisms such as pollinators or pest predators, thereby enhancing biological regulation (Burel et al.
172 2013, Garbach et al. 2017).

173 Such a biological diversity exists thanks to a diversity of practices, and associated knowledge (Jackson
174 et al. 2012, Leclerc and Coppens d'Eeckenbrugge 2012). The diversity of knowledge systems related to
175 agrobiodiversity is thus pivotal in biodiversity-based agriculture (Altieri 2004). Indeed, beyond the
176 diversity of biological resources, the way they are protected, chosen, multiplied, cultivated, or bred
177 largely drives the capacity of agroecosystems to provide contributions to human populations in space
178 and over time. These knowledge systems cover a variety of domains including agronomic management
179 (e.g. soil adaptation; Bazile et al. 2008, or synergies and competition between species; Isaac et al. 2018),
180 the processing and use of products, but also symbolic or relational aspects (Jackson et al. 2012). A key
181 aspect of agrobiodiversity management is its holistic and integrative dimension, i.e. how farmers
182 carefully evaluate trade-offs among its different contributions, some positive, some negative (Ango et
183 al. 2014), and also incorporate the complexity of their norms and values. Incentives for agrobiodiversity
184 management rarely account for the diversity of local worldviews including social, spiritual and symbolic
185 dimensions, while they affect a variety of domains of agrobiodiversity management including the spatial
186 organization of crops in farmers' fields and in the landscape (Bonnemaïson 1996), their selection beyond
187 a purely utilitarian motivation (Caillon and Lanouguère-Bruneau 2005) and their circulation answering
188 to social norms (Thomas and Caillon 2016).

189 Diversified agroecosystems are hence complex entities involving coupled ecological and social
190 interactions (Lescouret et al. 2015). They span different spatial scales, from the plot to the landscape
191 scale, as well as different time scales, and involve multiple institutional levels (Jackson et al. 2010).
192 These systems have emergent properties and unpredictable behavior, as short-term management actions
193 at the plot scale can have unexpected consequences for agroecosystem dynamics at larger spatial and
194 temporal scales, and vice versa. Collaboration and resource exchange are pivotal to sustain such systems
195 in which the stakeholders are strongly ecologically interdependent despite having divergent values and
196 objectives, and where knowledge is fragmented (Armitage et al. 2009). Fostering biodiversity-based
197 agriculture hence relies to a great extent on the capacity of stakeholders to exchange resources, learn
198 and collaborate across institutional levels, as well as across spatial and social units (Duru et al. 2015a,
199 Jackson et al. 2007).

200 Farmers' access to material and immaterial resources, including agrobiodiversity, is largely influenced
201 by their network of social relationships with different stakeholders (e.g., Bandiera and Rasul 2006).
202 These networks are qualified as "informal" in the literature because they are largely self-organized and
203 emerge without the support of official institutions (Coomes et al. 2015). They involve a variety of
204 individual stakeholders, primarily farmers, as well as organizational stakeholders such as private actors,
205 NGOs and extension services, or other rural development actors (McGuire and Sperling 2016, Isaac
206 2012, Hauck et al. 2016). Knowledge concerning these networks considerably progressed thanks to the
207 research field commonly denoted as social network analysis (SNA; Wasserman and Faust 1994). This
208 field has undergone major development in the social sciences since the 1990s, and has been applied in
209 a diversity of fields such as environmental management (Bodin 2017) and rural development
210 (Rockenbauch and Sakdapolrak 2017) over the last decade. SNA is dedicated to analyze the structure
211 of interactions between stakeholders, represented in the form of networks (Fig 2). Theoretical
212 frameworks and empirical and simulation studies were especially developed to understand how social
213 networks structure relates to different kinds of outcomes, such as material or immaterial resources
214 circulation, or collaboration success.

215 An increasing number of studies argue that supporting networking between farmers as well as with a
216 diversity of other stakeholders would enhance farmers' access to a diversified pool of knowledge (Duru
217 et al. 2015b), to associated agrobiodiversity (Hauck et al. 2016; Salliou and Barnaud 2017) and to crop
218 diversity (Almekinders and Louwaars 2002). Furthermore, studies building on social network theory
219 indicate that social networks shape the circulation of knowledge and crop, and also indirectly that of
220 associated organisms, hence playing on farm's access to agrobiodiversity in two ways: First, by driving
221 the maintenance, generation or decrease of agrobiodiversity at the landscape level, hence contributing
222 in determining the pool of agrobiodiversity available for farmers at this level (e.g., Pautasso et al. 2013).
223 Second, by determining the capacity of individual farmers to access this global pool of agrobiodiversity
224 (e.g., Kawa et al. 2013). In the following section, we summarize the role of social networks in farms'
225 access to the three components of agrobiodiversity, i.e. knowledge, associated diversity and crop
226 diversity. For each component, we review the literature exploring how the structure and composition of
227 social networks relate to farms' access to agrobiodiversity.



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Figure 2. Representation of different structural patterns of social networks. Nodes represent the social actors that can be of different kinds: individuals (e.g., farmers) or organizations. Ties represent their interactions, that can be of different kinds as well (e.g., collaboration, flows of material or immaterial resources).

Top: Simple networks (e.g., farmer-to farmer network): (A) **Distributed cohesive network.** The density of ties is high in this kind of network, where closed triangles are common building blocks. Centralization is low, meaning that there is little variation in the number of connections established by actors (degree) and network configuration is quite different from a star. Modularity is low, meaning that the network is not structured in subgroups. (B) **Centralized network.** In this kind of network, centralization is high (star-like network), meaning that a small number of actors have a very high number of connections (orange nodes) while the majority of them have few (blue nodes). Open triangles are common building blocks. The density and modularity are moderate to low. (C) **Modular network.** This kind of network structured in subgroups (orange, blue and green) arises through the preferential interaction of actors presenting the same characteristics (e.g., geographic location, ethnicity, gender). The building block is hence the interaction between two actors presenting the same characteristics. Centralization is low and modularity is high.

Bottom: Multilevel networks (e.g., network representing both interactions among farms, and between farms and institutional actors). (D) **Institutionally centralized network.** The network of interactions between levels presents a high centralization as a small number of institutional actors (square and green nodes) interact with farms (round and blue or orange nodes). The density within each layer is low as actors have limited interactions with their peers. Centralization is high in the farm layer as institutions usually rely on a few nodal farms for disseminating advice and planting material. (E) **Polycentric institutional network:** several institutions (square nodes) having interactions are connected to farms that act as brokers in their respective communities (orange, blue, green). The centralization of the network of interactions between levels is low. The density of interactions within each layer is higher than in (D), and the centralization is lower.

253 **2.1. Knowledge circulation networks and social learning**

254 Social learning is a key mechanism for agrobiodiversity management because of the complex and
255 unpredictable nature of the ecological processes involved. Facilitating social learning requires
256 developing networks of stakeholders with different knowledge systems and worldviews to create a
257 cooperative decision-making environment in which trust, understanding, and mutual reliance develop
258 over time (Stubbs and Lemon 2001). Social learning allows individuals to develop an understanding
259 that is less individualistic and takes place in wider social units or communities of practice (Reed et al.
260 2010). In most rural societies that practice biodiversity-based agriculture, practical and theoretical
261 knowledge related to agrobiodiversity management is built in a dynamic way through learning-by-doing
262 and social learning originating from multiple sources (Altieri 2004).

263 Fostering social learning entails not only collaboration among farmers and other local stakeholder within
264 and between communities, but also communication with institutional stakeholders at different levels of
265 governance (e.g. local, regional, national and international), and from different sectors (e.g. agriculture,
266 forest, the environment). Indeed, social learning relies on the involvement of stakeholders with a variety
267 of knowledge systems, experiences and perspectives concerning agrobiodiversity management in its
268 multiple dimensions, including functional, symbolic, or relational aspects. Social learning can be
269 supported by actions such as collective experimentation (Humphries et al. 2015), peer-to-peer exchanges
270 (Rosset et al. 2011), farm visits, and workshops involving farmers, and other stakeholders such as
271 extension agents and researchers, to build and share knowledge on biological resources, associated
272 agricultural techniques and practices, and landscape management.

273 The role of knowledge circulation networks structure in stakeholder access to knowledge diversity and
274 social learning has been widely studied in environmental management (Bodin 2017) and rural
275 development (Conley and Udry 2001) using SNA approaches. However, these frameworks have rarely
276 been applied to agrobiodiversity management. The few studies conducted on this topic indicate that
277 farmers connected to a wider range of stakeholders, especially to different rural development
278 organizations (Fig 2.E), tend to learn new practices and diversify their crops at both the plot (e.g. Isaac
279 2012) and landscape levels (Isaac and Matous 2017). This is in line with previous conceptual and
280 empirical works on social learning networks, which indicate that enhancing social learning requires a
281 balance between “bridging ties” connecting stakeholders or groups (Fig 2.C) with different knowledge
282 and worldviews, and “bounding ties” within groups of stakeholders sharing similar knowledge
283 (Davidson-Hunt 2006). Further application of existing frameworks (Berkes 2009) open promising
284 perspectives to improve our understanding of how social network composition and structure impacts
285 farmers’ access to a diversified pool of knowledge related to agrobiodiversity.

286 **2.2. Collaboration networks and access to associated biodiversity**

287 Associated agrobiodiversity includes a variety of organisms that play a key role in ecosystem services
288 including pollination, pest regulation, and soil fertility (Dainese et al. 2019). The enhancement of
289 associated biodiversity in agricultural landscapes requires changing individual farming practices in the
290 common interest, especially by limiting the use of pesticides and fertilizers. It also requires coordinating
291 land use practices at the landscape scale (Lichtenberg et al. 2017), with some non-intuitive
292 considerations such as e.g. the decrease of weed richness in crop fields with increasing weed diversity
293 in neighboring flower strips (Cordeau et al. 2012). A considerable body of literature indicates that
294 enhancing landscape heterogeneity by maintaining natural or semi-natural vegetation in agricultural
295 landscapes and a diversity of cropping systems is instrumental in boosting associated biodiversity (Burel
296 et al. 2013). Increasing the heterogeneity of landscape mosaics requires acting on its composition, but
297 also on its organization, i.e. the spatial arrangement of patches (Fahrig et al. 2011).

298 Enhancing farms' access to associated agrobiodiversity is hence primarily a matter of collaboration to
299 manage agricultural landscapes for enhancing ecological connectivity. However, although collaborative
300 landscape management has great promise for enhancing ecosystem service delivery in agroecosystems,
301 it has rarely been implemented up to now (Landis 2017). This lack of collaboration between stakeholders
302 at territorial and landscape level often appears as a bottleneck in the development of agroecological
303 farming. One reason for the lack of collaborative landscape management initiatives with the objective
304 of enhancing associated agrobiodiversity is that it raises major collaboration problems as it involves a
305 diversity of stakeholders at different institutional levels with competing interests and divergent views.
306 Furthermore, coordination involves delegation and devolution of power and authority, which is far from
307 easy to accomplish (Morrison et al. 2019). Collaborative landscape management for associated
308 biodiversity enhancement also raises social learning issues because of the complexity and large spatial
309 and temporal extent of the social-ecological processes involved (Salliou and Barnaud 2017).

310 The importance of social networks composition and structure in fostering collaboration for landscape
311 management has been widely studied in environmental management and governance (Guerrero et al.
312 2015), but rarely applied to associated agrobiodiversity management (Hauck et al. 2016). This literature
313 particularly emphasizes the importance of good alignment between social and ecological connectivity,
314 i.e. the existence of social ties between the stakeholders who manage ecologically-linked landscape units
315 (Bodin and Tengö 2012; Guerrero et al. 2013). Studies in this field further show that network
316 cohesiveness (Fig 2.A) is instrumental in building trust, which is a precondition for stakeholders to shift
317 their practices in the common interest and also to limit freeriding. Application of existing social-
318 ecological network frameworks for landscape management open promising perspectives for enhancing
319 associated biodiversity at the landscape scale (Hauck et al. 2016), hence favoring farms' access to this
320 resource.

321 **2.3. Seed circulation networks and access to crop diversity**

322 Accessing a wide range of crop species and varieties is the main production lever for small farms with
323 limited access to inputs (Altieri et al. 2012). Farms' access to crop diversity governs their capacity to
324 implement sustainable forms of agriculture based on ecosystem services (Gevers et al. 2019), as well as
325 their resilience in the face of social and environmental perturbations (McGuire and Sperling 2013;
326 Mwongera et al. 2014). Farms access to crop diversity encompasses two dimensions (Sperling et al.
327 2008). First, it is conditioned by the amount of diversity available at the landscape level and its
328 distribution, i.e. the variation in the composition of crop portfolios between farms. Studies in different
329 regions of the world converge to show that the diversity of crop species and farmers' varieties at the
330 landscape level, also called gamma diversity in ecology, is systematically larger than the diversity
331 cultivated at the individual farm level, or alpha diversity (e.g. Jarvis et al. 2008). This is due to the high
332 heterogeneity or variation in the composition of crop portfolios between farms, i.e., beta diversity.
333 Second, farms' access to crop diversity is also conditioned by their capacity to get additional crops out
334 of this pool. Social networks are pivotal in both dimensions of farms' access to crop diversity as they
335 drive the maintenance, generation and diffusion of crop diversity through seed multiplication, selection,
336 conservation, and circulation (Bellon 2004).

337 Self-organized crop seed circulation networks involving primarily farmers and other stakeholders such
338 as local seed sellers, but also private seed distributors, extension services, and NGOs play a key role in
339 this process (Coulibaly, Bazile, Sidibé 2014). Research on crop circulation networks has expanded over
340 the last decade (Pautasso et al. 2013, Calvet-Mir and Salpeteur 2016) building on SNA theoretical
341 background and methods. The use of SNA is far more developed for crop diversity study than for the
342 other components of agrobiodiversity, but the effect of the structure of crop circulation networks on
343 farms' access to crop diversity was rarely explored. The studies found in the literature focused on
344 different levels of crop diversity: i. the assemblages (or "portfolio") of crop species grown by farmers
345 (e.g. Abizaid et al. 2016), ii. the portfolio of farmers' varieties of a given species (e.g. Kawa et al. 2013),
346 or iii. the genetic composition of crop populations (e.g. Thomas et al. 2015). These studies used different
347 methodological approaches and metrics for describing the structure of crop circulation networks and
348 crop diversity. They described how crops circulate at different temporal scales, ranging from seeds that
349 circulated in the previous growing season to all the circulation events that occur over a farmer's lifetime.
350 Last, they focused on different scales, i.e. the individual or the farm scale, and the landscape scale.

351 At the farm scale, a small number of case studies explored how farmers' connectivity patterns when
352 exchanging seeds relate to their crop diversity. They dominantly used regression models to test how
353 farmers' centrality in the seed circulation network relates to the diversity of crops they grow, measured
354 using richness or other diversity indexes. Different centrality metrics were used to measure farmers'
355 centrality, the most frequent one being in-degree centrality, i.e. the number of entering connections.
356 These studies found different results concerning this relationship. Some studies, such as that of Calvet-

357 Mir et al. (2012) in homegardens in the Spanish Pyrenes found a positive correlation between the number
358 of crop species cultivated by farms and their number of entering connections. In other cases, such a
359 relationship was not validated, for instance in the Amazon for crop species in homegardens (Abizaid et
360 al. 2016) and for cassava farmers' varieties (Kawa et al. 2013), where the most central farmers were not
361 the ones with the more diverse portfolios.

362 At the landscape scale, some studies provided insights on how the global composition and structure of
363 the seed circulation networks affects crop diversity level and patterns. Most empirical studies at this
364 scale discuss qualitatively this relationship, describing network and crop diversity patterns separately
365 and then discussing how they relate to each other. Even though these studies do not test quantitatively
366 this relationship, they bring valuable insights on how the network structure relates to the availability of
367 crop diversity at the landscape scale and pave the way for future research. For instance, in Kenya,
368 Labeyrie et al. (2016) showed that seed flows were more frequent between farmers belonging to the
369 same ethnolinguistic group (i.e. homophily), and suggested this may explain the partition of farmers'
370 sorghum varieties according to these groups. They further argue that such a structure of seed circulation
371 could be in favor of a higher level of crop diversity at the collective level than expected if ties were
372 established randomly, as limited exchanges between ethnolinguistic groups is expected to impede the
373 uniformization of their crop portfolios and to contribute in maintaining specific varieties in each group
374 (Fig 2.C). At the genetic level, Thomas et al. (2012) reveals that the structure of the seed circulation
375 network of a historical bread wheat variety that circulated among French farmers during the 20th century
376 matches with the genetic composition of the variety sampled throughout the network. The same author
377 also reported on the impact of a centralized seed network, organized around a "core farmer" (Fig 2.B),
378 on crop genetic diversity (Thomas et al. 2015). By tracing a mixture of bread wheat developed and
379 diffused by this farmer to dozens of others, it showed that the same amount of genetic diversity was
380 maintained in the network of farmers growing this mixture as in the original farm, although a significant
381 differentiation was detected among these versions. This study illustrates how collectives - even
382 organized according to a centralized network - can simultaneously conserve genetic diversity
383 collectively and adapt it to local conditions after a seed flow event.

384 Last, some simulation studies also bring insights on the linkages between the global structure of seed
385 circulation networks and crop diversity patterns. The study of Barbillon et al. (2015) especially shows
386 that network density, centralization, and modularity (Fig 2.A to C) are key factors driving the circulation
387 and the persistence of crops in a system when applying the same dynamic model of
388 extinction/colonization to networks with different structural properties. Barbillon et al. study indicates
389 that different network structures have different implications for agrobiodiversity conservation
390 depending on the frequency of crop extinction at the farm level. Their results indicate that centralized
391 networks are more efficient in maintaining crop when extinction is frequent, while modular or

392 distributed cohesive networks are more efficient in other cases. These empirical and simulation studies
393 open up promising perspectives for understanding how the overall structure and composition of the crop
394 circulation networks drive the availability of a pool of crop diversity and its accessibility to farmers.

395 **3. Linking network structure to farm's access to agrobiodiversity: A framework for** 396 **crop diversity**

397 The literature review in the previous section showed that social networks play a key role in driving
398 farms' access to the three components of agrobiodiversity, i.e. knowledge, associated diversity and crop
399 diversity. However, how the composition and structure of social networks relate to agrobiodiversity
400 access remains poorly understood. A promising way to advance our understanding of this relationship
401 would be to integrate the valuable insights provided by the literature on social-ecological networks. This
402 research field emerged about fifteen years ago (Janssen et al. 2006), and developed conceptual
403 frameworks to explore the reliance of environmental management outcomes on the kind of stakeholders
404 involved, their relationships, and the way their interactions with one another and with the natural
405 resources are framed (Bodin 2017). Research on social-ecological networks brought major advances
406 on representing the complexity of interactions between human societies and their environment, and
407 deciphering the processes driving the sustainability of social-ecological systems (Bodin et al. 2016). By
408 jointly considering ecological and social interactions, some structural properties of SEN enhancing
409 management efficiency and strengthening the sustainability and resilience of social-ecological systems
410 in the face of perturbations have been identified (Barnes et al. 2017). The importance of stakeholders'
411 interactions patterns at the local level have been highlighted in particular, along with their 'vertical'
412 interactions with institutional stakeholders (Cohen et al. 2012; Sayles and Baggio 2017).

413 Existing social-ecological network frameworks can be adapted and applied to analyze the processes
414 driving farms' access to two out of the three agrobiodiversity components, i.e., collaboration for the
415 management of associated diversity and social learning. However, it is not the case for crop diversity,
416 which presents specificities and for which a dedicated framework is needed to guide future research and
417 allow comparing results. Indeed, existing frameworks mainly focus on common-pool or open access
418 resources, which present characteristics and management issues different from those of crop diversity.
419 They were designed to understand how the structure of social-ecological interaction patterns affects the
420 collaboration and social learning for limiting the depletion of natural resources, which is a different
421 objective than that of enhancing agrobiodiversity.

422 In the case of crop diversity, a first specificity is that the overall level of diversity available at the
423 collective level does not only depend on the capacity of stakeholders to collaborate for a sustainable use
424 of the resource through the modification of their individual practices, but also on their capacity to
425 organize the exchange of crop between them. Hence, for crop diversity, collaboration does not solely

426 intervene in the regulation and coordination of individual practices, but also in the circulation of planting
427 material. Furthermore, unlike the resources usually studied in social-ecological network literature (e.g.,
428 fish, water, natural vegetation), the availability of a diverse pool of crops at the collective level does not
429 only require enhancing the biological connectivity, i.e. seed flows, between farms. It rather depends on
430 a compromise: intense crop circulation between farms leads to the uniformization of cultivated plants,
431 while low connectivity can lead to the extinction or inbreeding of crop populations. Last, previous
432 social-ecological network frameworks did not address the issue of individual's resources access as they
433 mostly focus on the availability and dynamic of the resource at the community level, while this issue is
434 pivotal for crop diversity. In this section, we identify potential contributions from the social-ecological
435 network literature to the study of network characteristics affecting farms' access to crop diversity, and
436 we propose a dedicated framework.

437 **3.1. Insights from social-ecological networks research on crop diversity access**

438 A first insight from the literature on social-ecological networks for agrobiodiversity management is its
439 substantial conceptual background on the social network structures of importance for environmental
440 management. This literature especially emphasizes the importance of the diversity of stakeholders
441 involved in resource management and highlights the importance of connectivity patterns: i. between
442 farms belonging to different communities or groups, and ii. between farms and organizations such as
443 NGOs, extension services or other private actors (Fig. 2. D and E). Indeed, most social network studies
444 on crop diversity management focus on connectivity patterns within rural communities (e.g., Abizaid et
445 al. 2016; Calvet-Mir et al. 2012). They rarely examine the connectivity between communities (e.g.,
446 Abizaid et al. 2018, Isaac et al. 2014) and with organizations or institutions (Isaac 2012), while these
447 "bridging" ties are considered to be key in environmental management (Ernstson et al. 2010; Rathwell
448 and Peterson 2012) and in rural development (Krishna 2003).

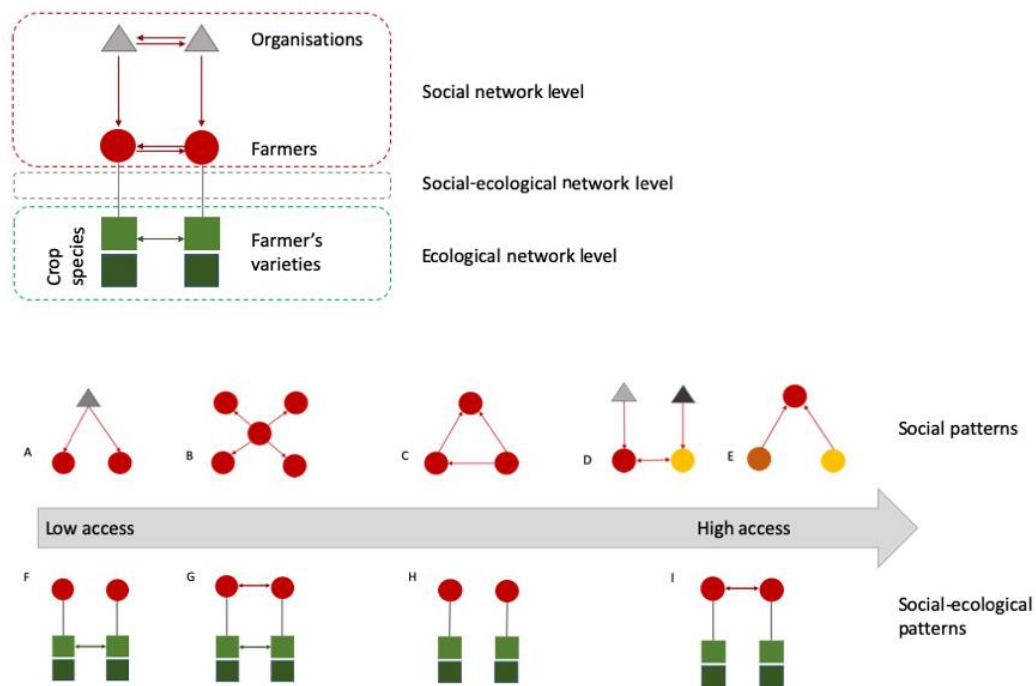
449 Second, another interesting insight from social-ecological network research is the possibility of
450 incorporating ecological ties in representations of the networks involved in crop circulation. Indeed, our
451 literature review showed that research on crop diversity management has mostly focused on social
452 connectivity between farms. Little attention has been paid to representing the ecological relationships
453 between farms' crop portfolios, mainly through gene flows, which we believe is an important gap in
454 research on crop circulation networks. Representing both farms and crop portfolios in the form of
455 interconnected "social-ecological" networks would allow the simultaneous analysis of social-,
456 ecological- and integrated social-ecological relationships. We believe that developing this social-
457 ecological representation of crop diversity management would pave the way for a better understanding
458 of the structure-outcome relationship, as suggested by Bohan et al. (2013) more generally for
459 agroecosystems. In the following section, we thus propose a social-ecological framework for
460 representing how the social and social-ecological interaction patterns affect farm's access to crop

461 diversity. Our framework will help address the management “dilemma”, i.e. help identify the social-
462 ecological network configurations that create the necessary conditions for a good balance between the
463 maintenance and generation of crop diversity at the landscape level, and its accessibility to farmers.

464 **3.2. A social-ecological network framework for crop diversity management**

465 Adhering to the social-ecological network representation (Fig 3), crop circulation networks consist of
466 social nodes that represent either individual farmers or organizations, and ecological nodes that represent
467 the portfolios of farmers’ varieties for each crop species cultivated in the farms. Farmers’ varieties being
468 here defined as the basic unit identified and named by farmers at the infraspecific level for management
469 (Berg 2009). Two kinds of social nodes can be distinguished: farms, characterized by their social,
470 economic, biophysical attributes, and organizations or institutional stakeholders who diffuse crop seeds.
471 Ties between social nodes represent different kinds of social relationships they can mobilize to access
472 or exchange seed, including economic relationships. Social ties are directed, reflecting that depending
473 on the nature of the relationship, seed flows can be unidirectional or reciprocated. Lastly, ecological ties
474 reveal non human-mediated gene flows between crop portfolios, which can result for instance from
475 pollen flows between neighboring fields managed by different farmers.

476 Based on the literature reviewed (section 2.3), we expect the structure of social-ecological networks to
477 play at two levels on farms’ access to crop diversity, defined as their ability to get additional crops out
478 of the global pool available at the landscape level. First, the structure and composition of the global
479 network is expected to determine beta diversity, i.e. the heterogeneity in crop portfolio composition at
480 the landscape scale. This is further supported by theoretical models of community ecology, with
481 processes comparable to those of seed circulation, indicating that different network topologies between
482 ecological patches have different impacts on alpha and beta diversities (Economio and Keitt 2008).
483 Second, the position of each farm in the network is expected to determine its capacity to access this
484 additional pool of diversity available at the landscape level, a finding also reminiscent of similar
485 conclusions in community ecology (Economio and Keitt 2010). Hence, different structures of these
486 social-ecological networks would result in different outcomes for farms’ access to crop diversity. Below,
487 we build on the literature reviewed in the previous sections to identify network patterns (Fig 3, bottom)
488 expected to affect farms’ access to crop diversity.



489
 490 **Figure 3. Social-ecological network representation of interactions involved in farm's access to crop diversity**
 491 **(Top), and local network patterns expected to affect farms' access to crop diversity (Bottom).** Nodes
 492 represent: i. the portfolios of farmers' variety for the different crop species grown in farms (green squares, the
 493 different shades of green represent different species), ii. farmers (red circles), and iii. organizations (triangles)
 494 involved in crop diffusion. Edges represent the ecological (i.e. gene flows, green), social (red), and social-
 495 ecological (grey) interactions. For social ties, arrows indicate the direction of interactions, stemming from the
 496 "source" or "donor" of seed to the "target" or "recipient".

497 The way the social interactions are framed between farmers as well as with other stakeholders is
 498 expected to strongly determine the beta diversity, i.e. the variation in crop portfolio composition at the
 499 landscape level, and its accessibility for farmers. Network centralization, i.e. the fact that a small number
 500 of farmers (Fig. 3.B) or organizations (Fig. 3.C) are diffusing seeds to the rest of the farmers, is expected
 501 to lead to the uniformization of crops between farms. Hence, the additional diversity of crops available
 502 at the collective level is expected to be limited as compared to that grown individually by farms.
 503 Furthermore, centralization may result in inequality of access to this resource by farmers (Ricciardi
 504 2015), as some of them may not be connected to the core seed distributors. Centralized networks are
 505 thus expected to decrease farms' access to crop diversity.

506 Conversely, the involvement of a variety of institutional stakeholders (Fig. 3.D) in crop management
 507 networks, or that of farms presenting different characteristics (Fig. 3.E), e.g., socio-cultural, economic,
 508 agroecological, is hypothesized to enhance the heterogeneity in crop diversity distribution at the
 509 landscape level. Indeed, this diversity of stakeholders is a source of diversity for crops, grown in

510 different conditions and according to different criteria. Environmental research has shown that cross-
511 scale brokers connecting, for example, local, regional, national management levels are keys to
512 innovation and to the introduction of new resources (Cohen et al. 2012; Hamilton et al. 2020), but their
513 role has rarely been investigated in crop diversity management (Isaac 2012). Furthermore, social-
514 ecological network literature also highlights the role of brokers who connect different communities, i.e.
515 groups of stakeholders closely connected together while loosely connected to other groups, in the
516 introduction and diffusion of new resources (Barnes et al. 2016; Bodin and Norberg 2005; Granovetter
517 1973). Such processes have been rarely explored in crop diversity studies, but some studies already
518 suggest such brokers play a key role in the introduction of new crops and practices, hence enhancing the
519 diversity available at the collective level (e.g., Valente 1996, Isaac et al. 2014).

520 Last, social-ecological network literature provides multiple illustrations of the key role of cohesion in
521 social networks (Fig 3. C - also often called closure) in the diffusion of resources within communities
522 (Ernstson et al. 2008; Olsson et al. 2004). Cohesion is expected to enhance farmers' access to crop
523 diversity, but it can lead to the uniformization of crop species and varieties between farms over time. In
524 highly cohesive networks, the additional diversity of crops available at the collective level, i.e., the
525 average beta diversity between a single farm and the rest of the network, may hence be limited as
526 compared to that grown in one farm (i.e. the average alpha diversity). Hence, finding the right balance
527 between cohesion within communities, and connectivity with other communities and institutional
528 stakeholders, is expected to be crucial for enhancing access to crop diversity for farmers.

529 Social-ecological interaction patterns are also expected to drive farms' access to crop diversity. In the
530 case where farms grow ecologically connected crop portfolios (Fig 3. F-G), the beta diversity is expected
531 to be low because gene flows lead to the uniformization of crops between them. Beta diversity will be
532 even lower when farmers are socially connected (G) and have higher chances to exchange seed. Last,
533 when farms grow crop portfolios ecologically isolated from one another (Fig 3.H-I), the beta diversity
534 at the landscape level is expected to be high, because differences between farms' crop portfolios will be
535 maintained, and even enhanced through local adaptation over time. However, if farms are not socially
536 connected, this beta diversity at the landscape level cannot be exploited and accessed by farmers because
537 of the absence of social connectivity between them (Fig 3.H). On the contrary, if farms are socially
538 connected, then this pool will be accessible for farmers (Fig 3.I).

539 Beyond these social-ecological connectivity patterns, crop reproductive biology, crop environment and
540 cultivation practices also impact beta diversity. Crops present differences in their reproductive biology,
541 some being rather allogamous (i.e. dominantly outbreeding), others being rather autogamous (i.e.
542 dominantly self-breeding), or clonally propagated. These differences have strong impacts on the
543 intensity of gene flows and crossing between crop varieties, which can accelerate the uniformization of
544 crops at the infra specific level and thus decrease beta diversity. Then, local adaptive processes,

545 especially adaptation to local soils, climate, biotic environment and cultivation practices can enhance
546 the differentiation of crops between farms, and increase beta diversity. Such a local adaptation process
547 can even lead to the differentiation of crops cultivated in different conditions despite seed flows between
548 farms (Pressoir and Bertaud, 2004; Thomas et al. 2015).

549 **4. Conclusion and Perspectives**

550 In this article, we have detailed the key role played by social networks involving multiple stakeholders
551 in farms' access to agrobiodiversity, including knowledge, associated diversity of beneficial organisms
552 and crop diversity. We reviewed studies investigating the relationship between the structure of social
553 networks affecting agrobiodiversity circulation and their outcomes, i.e. the different dimensions of
554 agrobiodiversity access. This review reveals a major gap of knowledge concerning this relationship, as
555 it was never explored beyond local case studies and rare simulation studies. In response to this lack of
556 operational knowledge of general scope, this article identifies the contribution that social-ecological
557 network frameworks could bring, and lays the foundations of a social-ecological network framework
558 dedicated to crop diversity access as previous frameworks developed for environmental management
559 are not appropriate to deal with its specificities. This framework is expected to contribute in guiding the
560 implementation of future research aiming at building generic knowledge, based on large-scale cross-
561 sectional surveys or simulation studies.

562

563 Obtaining more insights into how social networks impact farms' access to crop diversity has major
564 implications for agricultural policies and development programs that usually opt for centralizing the
565 dissemination of biological resources and associated knowledge and with little consideration for existing
566 social organizations (Bocci and Chable 2009; Gevers et al. 2019). This governance option is at risk as
567 centralized management limits farmers' capacity to rapidly respond to social and ecological
568 transformations and to cope with uncertainty (Armitage et al. 2009). New management and governance
569 options should thus be developed to support biodiversity-based agriculture that would rely on
570 collaboration between the different stakeholders involved, grounded on local farmer networks (Coolsaet
571 2015). However, in order to have more impact on public policies, farmers also need to be more
572 connected with stakeholders across institutional levels.

573 An increasing number of papers call for a shift from the currently prevailing top-down vision of
574 agricultural support through the diffusion of innovations from research and development to the co-
575 construction of sustainability trajectories by including local knowledge, practices and collective
576 organizations (Berthet et al. 2016; Duru et al. 2015b; Klerkx et al. 2010). Operational approaches
577 supporting the collaborative management of agrobiodiversity remain rare, with some examples related
578 to participatory plant breeding (Chable et al. 2014; Cecarelli and Grando 2020), or to collective

579 landscape management for associated biodiversity enhancement (e.g., Steingröver et al. 2010). In most
580 cases, these processes are poorly supported at the institutional level, whether for crop diversity (Berthet
581 et al. 2020) or associated biodiversity (Leventon et al. 2017). Furthermore, these initiatives face multiple
582 obstacles to collaboration, among which power imbalance is a major issue (Porcuna-Ferrer et al. 2020).
583 This calls for the development of participatory approaches that enhance the ability of stakeholder groups
584 to set common objectives and collectively explore a diversity of solutions.

585 The development of such participatory approaches encompasses three key dimensions. The first is
586 enhancing social learning to enable stakeholders to become aware of their interdependence concerning
587 the different components of agrobiodiversity, and to understand the complex interactions that drive the
588 availability of agrobiodiversity at the collective level and its accessibility to farmers (Bazile 2006). The
589 complexity of interactions hampers their ability to grasp the collective dimension of agrobiodiversity
590 management, which, in turn, limits their willingness to collaborate. Enhancing social learning requires
591 dedicated methods and interactive tools to enable dialogue between the knowledge systems of the
592 different stakeholders: scientific, technicians and farmers. The second dimension is developing
593 dedicated tools to explore scenarios and to discuss the consequences of different network structures on
594 the availability and accessibility of agrobiodiversity to farmers (Chable et al. 2020; Abrami et al 2008).
595 The third dimension is building trust among stakeholders to encourage the collective definition of
596 desirable outcomes and to nurture their willingness to get involved in a genuine collaborative
597 management of agrobiodiversity (Demeulenaere et al. 2018; Padmanabhan 2008).

598 Designing and using simulation models with stakeholders can support such transformative change
599 processes by providing a boundary object or negotiating artifact that allows participants to deliberate
600 through a multi-interpretable, consistent, transparent, and verifiable representation of reality (van
601 Bruggen et al., 2019). In their review of methods for studying seed exchange networks in relation to
602 agrobiodiversity, Pautasso and colleagues (2013) considered both participatory approaches and
603 simulation models as standalone methods located at the opposite corners of a two-dimensional space
604 defined by a qualitative/quantitative axis and an empirical/theoretical axis. In fact, the advantages of
605 combining the two types of methods were already demonstrated several years previously (Voinov and
606 Bousquet 2010). In socio-ecological science, agent-based simulation models (ABMs) have become the
607 preferred tool as they can represent stakeholders of a given socio-ecosystem as decision-making entities
608 interacting in a multi-level spatially-explicit virtual environment (Lippe et al. 2019). Used in a
609 participatory way, as promoted by companion modelling, among other approaches (Barreteau et al
610 2014), the stakeholders represented as agents in the model react when viewing the simulation. To
611 stimulate interactions among them, participants can be invited to act out their own role in stylized
612 situations created by the organizers in role-playing sessions (Bousquet et al. 2002).

613 In Thailand, such participatory simulation workshops with stakeholders involved in the seed system in
614 Ubon Ratchathani Province were organized to collectively explore how the structure and functioning of
615 the provincial seed system affect the dynamics of local rice agrobiodiversity, with the aim of promoting
616 a more balanced partnership between the stakeholders of the system (Abrami et al. 2008). In Mali, a
617 similar approach was used to analyze the functioning of the farmer seed system, and enhanced collective
618 learning for crop diversity management (Bazile and Abrami 2008). The use of social-ecological network
619 analysis and modelling in participatory approaches have a strong potential for exploring with
620 stakeholders how the way their interactions are framed affect their access to agrobiodiversity. Such
621 participatory modelling approaches hence open promising perspectives for developing agrobiodiversity
622 management and governance options that are better adapted to biodiversity-based agriculture.

623 **5. Acknowledgements**

624 The authors gratefully acknowledge researchers in the MIREs network, funded by INRAE, and the
625 GDR ReSoDiv, funded by the CNRS, for rich discussions that significantly contributed to this paper.
626 Special thanks to Pierre Barbillon and Saint-Clair Chabert-Liddell for their help with the figures, and to
627 Camille Nous for her meaningful insights. We also thank two anonymous reviewers for their
628 constructive suggestions that significantly improved this paper.

629 **6. Declarations**

630 **Availability of data and materials:** Not applicable.

631 **Competing interests:** The authors have no conflicts of interest to declare that are relevant to the content
632 of this article.

633 **Funding:** The coordination of this work was aided by training facilities provided by CIRAD which
634 associated senior and junior researchers.

635 **Authors' contribution:** Conceptualization, V.L, J.B, M.A, C.L.P; Literature search, V.L, J.M, C.L.P;
636 Writing –Original Draft, V.L, C.L.P; Writing –Review & Editing, M.A. D.B, Ö.B, S.C, C.L, S.L, J.M,
637 F.M, M.T; Funding Acquisition, V.L.

638 **Ethical approval:** Not applicable (review).

639 **7. References**

640 Abizaid C, Coomes OT, Perrault-Archambault M (2016) Seed sharing in Amazonian indigenous rain
641 forest communities: a social network analysis in three Achuar villages. *Peru Hum Ecol* 44(5):577–594

642 Abizaid C, Coomes OT, Takasaki Y, Arroyo-Mora JP (2018) Rural Social Networks along Amazonian
643 Rivers: Seeds, Labor and Soccer among Communities on the Napo River. *Peru Geogr Rev* 108(1):92–
644 119

645 Abrami G, Bazile D, Trébuil G, Le Page C, Bousquet F, Dionnet M, Vejpas C (2008) Accompagner
646 l'évolution des systèmes semenciers céréaliers au Mali et en Thaïlande. *Cah Agric* 17(2):210-215

647 Almekinders C J, Louwaars N P (2002) The importance of the farmers' seed systems in a functional
648 national seed sector. *J New Seeds* 4(1-2) 15-33

649 Altieri MA (2004) Linking ecologists and traditional farmers in the search for sustainable agriculture.
650 *Front Ecol Environ* 2(1):35–42

651 Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for
652 smallholder farmers: contributions to food sovereignty. *Agron Sustain Dev* 32(1):1–14

653 Anderman TL, Remans R, Wood SA, DeRosa K, DeFries RS (2014) Synergies and tradeoffs between
654 cash crop production and food security: a case study in rural Ghana. *Food Secur* 6(4):541–554

655 Ango TG, Börjeson L, Senbeta F, Hylander K (2014) Balancing ecosystem services and disservices:
656 Smallholder farmers' use and management of forest and trees in an agricultural landscape in
657 southwestern Ethiopia. *Ecol Soc* 19(1):30. doi:10.5751/ES-06279-190130

658 Armitage DR, Plummer R, Berkes F, Arthur RI, Charles AT, Davidson-Hunt IJ, Diduck AP, Doubleday
659 NC, Johnson DS, Marschke M (2009) Adaptive co-management for social–ecological complexity. *Front*
660 *Ecol Environ* 7(2):95–102

661 Bandiera O, Rasul I (2006) Social networks and technology adoption in northern Mozambique. *Econ J*
662 116(514):869–902. doi:10.1111/j.1468-0297.2006.01115.x

663 Barbillion P, Thomas M, Goldringer I, Hospital F, Robin S (2015) Network impact on persistence in a
664 finite population dynamic diffusion model: application to an emergent seed exchange network. *J Theor*
665 *Biol* 365(1):365–376

666 Barnes M, Bodin Ö, Guerrero A, McAllister R, Alexander S, Robins G (2017) The social structural
667 foundations of adaptation and transformation in social–ecological systems. *Ecol Soc* 22(4):16.
668 doi:10.5751/ES-09769-220416

669 Barnes ML, Lynham J, Kalberg K, Leung P (2016) Social networks and environmental outcomes. *Proc*
670 *Natl Acad Sci* 113(23):6466–6471

671 Barreteau O, Bousquet F, Etienne M, Souchère V, d'Aquino P (2014) Companion modelling: a method
672 of adaptive and participatory research. In: *Companion modelling: a participatory approach to support*
673 *sustainable development*. Springer, Dordrecht

674 Bazile D 2006. *State-farmer partnerships for seed diversity in Mali*. IIED, Londres

675 Bazile D, Abrami G (2008) Des modèles pour analyser ensemble les dynamiques variétales du sorgho
676 dans un village malien. *Cah Agric* 17(2):203-209

677 Bazile D, Dembélé S, Soumaré M, Dembélé D (2008) Utilisation de la diversité variétale du sorgho
678 pour valoriser la diversité des sols au Mali. *Cah Agric* 17(2):86–94

679 Bellon M (2004) Conceptualizing Interventions to Support On-Farm Genetic Resource Conservation.
680 *World Dev* 32(1):159-172. doi:10.1016/j.worlddev.2003.04.007

681 Berg T (2009) Landraces and folk varieties: a conceptual reappraisal of terminology. *Euphytica* 166
682 (3):423-30.

683 Berkes F (2009) Evolution of co-management: role of knowledge generation, bridging organizations
684 and social learning. *J Environ Manage* 90(5):1692–1702

685 Berthet ET, Bosshardt S, Malicet-Chebbah L, van Frank G, Weil B, Segrestin B, Rivière P, Bernard L,
686 Baritoux E, and Goldringer I (2020) Designing Innovative Management for Cultivated Biodiversity:
687 Lessons from a Pioneering Collaboration between French Farmers, Facilitators and Researchers around
688 Participatory Bread Wheat Breeding. *Sustainability* 12(2):605

689 Berthet ET, Barnaud C, Girard N, Labatut J, Martin G (2016) How to foster agroecological innovations?
690 A comparison of participatory design methods. *J Environ Plan Manag* 59(2):280–301

691 Bocci R, Chable V (2009) Peasant seeds in Europe: stakes and prospects. *J Agric Environ Int Dev* 103(1-
692 2):81–93

693 Bodin Ö (2017) Collaborative environmental governance: Achieving collective action in social-
694 ecological systems. *Science* 357:eaan1115

695 Bodin Ö, Robins G, Mcallister RRJ, Guerrero AM, Crona B, Tengö M, Lubell M (2016). Theorizing
696 benefits and constraints in collaborative environmental governance: a transdisciplinary social-ecological
697 network approach for empirical investigations. *Ecol. Soc.* 21(1):40

698 Bodin Ö, Crona BI (2009) The role of social networks in natural resource governance: What relational
699 patterns make a difference? *Glob Environ Change* 19(3):366–374

- 700 Bodin Ö, Norberg J (2005) Information network topologies for enhanced local adaptive management.
701 *Environ Manage* 35(2):175–193
- 702 Bodin Ö, Tengö M (2012) Disentangling intangible social–ecological systems. *Glob Environ Change*
703 22(2):430–439
- 704 Bohan DA, Raybould A, Mulder C et al. (2013) Networking agroecology: integrating the diversity of
705 agroecosystem interactions. *Adv Ecol Res* 49(1):1-67
- 706 Bonnemaïson J (1996) *Gens de pirogue et gens de la terre*. Editions de l'ORSTOM, Paris
- 707 Bousquet F, Barreteau O, D'Aquino P, Etienne M, Boissau S, Aubert S, Le Page C, Babin D, Castella
708 JC (2002) Multi-agent systems and role games: collective learning processes for ecosystem
709 management. In: *Complexity and ecosystem management. The theory and practice of multi-agent*
710 *systems*. Edward Elgar Publishing, Cheltenham
- 711 Burel F, Aviron S, Baudry J, Le Féon V, Vasseur C (2013) The structure and dynamics of agricultural
712 landscapes as drivers of biodiversity. In: *Landscape Ecology for Sustainable Environment and Culture*.
713 Springer, Dordrecht.
- 714 Caillon S, Lanouguère-Bruneau V (2005) Gestion de l'agrobiodiversité dans un village de Vanua Lava
715 (Vanuatu): stratégies de sélection et enjeux sociaux. *J Société Océan* 120-121:129-148.
716 doi:10.4000/jso.451
- 717 Calvet-Mir L, Calvet-Mir M, Molina JL, Reves-Garcia V (2012) Seed exchange as an agrobiodiversity
718 conservation mechanism. A case study in Vail Fosca, Catalan Pyrenees, Iberian Peninsula. *Ecol Soc*
719 17(1):29. doi:10.5751/ES-04682-170129
- 720 Calvet-Mir L, Salpeteur M (2016) Humans, plants, and networks: A critical review. *Env Soc* 7(1):107-
721 128. doi:10.3167/ares.2016.070107
- 722 Ceccarelli S, Grando S (2020). Participatory plant breeding: Who did it, who does it and where? *Exp*
723 *Agric* 56(1):1-11
- 724 Chable V, Nuijten E, Costanzo A, et al. (2020) Embedding cultivated diversity in society for agro-
725 ecological transition. *Sustainability*, 12(3):784
- 726 Chable V, Dawson J, Bocci R, Goldringer I (2014) Seeds for organic agriculture: Development of
727 participatory plant breeding and farmers' networks in France. In: *Organic Farming, Prototype for*
728 *Sustainable Agricultures*. Springer, Dordrecht

729 Clough Y, Barkmann J, Jührbandt J et al. (2011) Combining high biodiversity with high yields in
730 tropical agroforests. *Proc Natl Acad Sci* 108(20):8311-8316.

731 Cohen PJ, Evans LS, Mills M (2012) Social networks supporting governance of coastal ecosystems in
732 Solomon Islands. *Conserv Lett* 5(5): 376–386.

733 Conley T, Udry C (2001) Social learning through networks: The adoption of new agricultural
734 technologies in Ghana. *Am J Agric Econ* 83(3):668–673

735 Coolsaet B (2015). Transformative participation in agrobiodiversity governance: making the case for an
736 environmental justice approach. *J of Agric and Environ Ethics* 28(6):1089-1104

737 Coomes OT, McGuire SJ, Garine E, Caillon S, Mckey D, Demeulenaere E, Jarvis D, Aistara G, Barnaud
738 A, Clouvel P (2015) Farmer seed networks make a limited contribution to agriculture? Four common
739 misconceptions. *Food Policy* 56(1):41–50

740 Cordeau S, Petit S, Reboud X, Chauvel, B (2012) Sown grass strips harbour high weed diversity but
741 decrease weed richness in adjacent crops. *Weed Res* 52(1):88-97

742 Coulibaly H, Bazile D, Sidibé A (2014) Modelling seed system networks in Mali to improve farmers
743 seed supply. *Sustain Agric Rese*, 3(4):18-32

744 Dainese M, Martin EA, Aizen MA. et al. (2019). A global synthesis reveals biodiversity-mediated
745 benefits for crop production. *Sci Adv* 5(10): eaax0121

746 Davidson-Hunt IJ (2006). Adaptive learning networks: developing resource management knowledge
747 through social learning forums. *Hum Ecol* 34(4):593-614.

748 DeClerck FA, Jones SK, Attwood S, Bossio D, Girvetz E, Chaplin-Kramer B, Norieg IL (2016)
749 Agricultural ecosystems and their services: the vanguard of sustainability? *Curr Opin Env Sustain*
750 23(1):92-99.

751 Demeulenaere É, Rivière P, Hyacinthe A, Baltassat R, Baltazar S, Gascuel JS, Lacanette J, Montaz H,
752 Pin S, and Ranke O (2017). Participatory plant breeding and scale issues. On a collaboration between
753 farmer plant breeders and field geneticists. *Natures Sciences Sociétés* 25(4):336–346.

754 Duru M, Therond O, Fares M (2015a) Designing agroecological transitions; A review. *Agron Sustain*
755 *Dev* 35(4):1237-1257. doi:10.1007/s13593-015-0318-x

756 Duru M, Therond O, Martin G, Martin-Clouaire R, Magne MA, Justes E, Journet EP, Aubertot JN,
757 Savary S, Bergez JE (2015b). How to implement biodiversity-based agriculture to enhance ecosystem
758 services: a review. *Agron Sustain Dev* 35(4):1259–1281. doi:10.1007/s13593-015-0306-1

759 Economo EP, Keitt TH (2008) Species diversity in neutral metacommunities: a network approach. *Ecol*
760 *lett* 11(1):52-62

761 Economo EP, Keitt TH (2010) Network isolation and local diversity in neutral metacommunities. *Oikos*,
762 119(1):1355-1363

763 Ernstson H, Barthel S, Andersson E, Borgström ST (2010) Scale-crossing brokers and network
764 governance of urban ecosystem services: the case of Stockholm. *Ecol Soc* 15(4):28

765 Ernstson H, Sörlin S, Elmqvist T (2008) Social movements and ecosystem services—The role of social
766 network structure in protecting and managing urban green areas in Stockholm. *Ecol Soc* 13(2):39

767 Fahrig L, Baudry J, Brotons L, Burel FG, Crist TO, Fuller RJ, Sirami C, Siriwardena GM, Martin JL
768 (2011) Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecol Lett*
769 14(2):101–112

770 Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. *Annu.*
771 *Rev. Environ. Resour.* 30(1): 441 73

772 Frison EA (2016) From uniformity to diversity: a paradigm shift from industrial agriculture to
773 diversified agroecological systems. IPES, Louvain-la-Neuve

774 Garbach K, Milder JC, DeClerck FA, Montenegro de Wit M, Driscoll L, Gemmill-Herren B (2017)
775 Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological
776 intensification. *Int J Agric Sustain* 15(1): 11-28.

777 Gevers C, van Rijswick HF, Swart J (2019) Peasant seeds in France: Fostering a more resilient
778 agriculture. *Sustainability* 11(11):3014. doi:10.3390/su11113014

779 Granovetter M (1973) The strength of weak ties. *Am J Sociol* 78(1):1360–1380

780 Guerrero A, Bodin Ö, McAllister R, Wilson K (2015) Achieving social-ecological fit through bottom-
781 up collaborative governance: an empirical investigation. *Ecol Soc* 20(4):41. doi:10.5751/ES-08035-
782 200441

783 Guerrero AM, McAllister R, Corcoran J, Wilson KA (2013) Scale Mismatches, Conservation Planning,
784 and the Value of Social-Network Analyses. *Conserv Biol* 27(1):35–44

785 Halewood M, Noriega IL, Louafi S (2013) The global crop commons and access and benefit-sharing
786 laws: examining the limits of international policy support for the collective pooling and management of
787 plant genetic resources. In *Crop Genetic Resources as a Global Commons*. Routledge, New-York

788 Hamilton M, Hileman J, Bodin Ö (2020) Evaluating heterogeneous brokerage: New conceptual and
789 methodological approaches and their application to multi-level environmental governance networks.
790 *Soc Netw* 61(1):1–10

791 Hatt S, Boeraeve F, Artru S, Dufrêne M, Francis F (2018) Spatial diversification of agroecosystems to
792 enhance biological control and other regulating services: An agroecological perspective. *Sci Total*
793 *Environ* 621(1):600-611

794 Hauck J, Schmidt J, Werner A (2016) Using social network analysis to identify key stakeholders in
795 agricultural biodiversity governance and related land-use decisions at regional and local level. *Ecol Soc*
796 21 (2):49. doi:10.5751/ES-08596-210251

797 Humphries S, Rosas JC, Gómez M, Jiménez J, Sierra F, Gallardo O, Avila C, Barahona M (2015)
798 Synergies at the interface of farmer–scientist partnerships: agricultural innovation through participatory
799 research and plant breeding in Honduras. *Agric Food Secur* 4(1):27. doi:10.1186/s40066-015-0046-0

800 Isaac ME (2012) Agricultural information exchange and organizational ties: the effect of network
801 topology on managing agrodiversity. *Agric Syst* 109:9–15

802 Isaac ME, Anglaaere LC, Akoto DS, Dawoe E (2014) Migrant farmers as information brokers:
803 agroecosystem management in the transition zone of Ghana. *Ecol Soc* 19(2):56. doi:10.5751/ES-06589-
804 190256

805 Isaac ME, Cerda R, Rapidel B, Martin AR, Dickinson AK, Sibelet N (2018) Farmer perception and
806 utilization of leaf functional traits in managing agroecosystems. *J Appl Ecol* 55(1):69–80

807 Isaac ME, Matous P (2017) Social network ties predict land use diversity and land use change: a case
808 study in Ghana. *Reg Environ Change* 17(16):1823–1833

809 Isbell F, Adler PR, Eisenhauer N, Fornara D, Kimmel K, Kremen C, Letourneau DK, Liebman M, Polley
810 HW, Quijas S (2017) Benefits of increasing plant diversity in sustainable agroecosystems. *J Ecol*
811 105(4):871–879

812 Jackson L, van Noordwijk M, Bengtsson J, Foster W, Lipper L, Pulleman M, Said M, Snaddon J,
813 Vodouhe R (2010) Biodiversity and agricultural sustainability: from assessment to adaptive
814 management. *Curr Opin Environ Sustain* 2 (1-2):80–87

815 Jackson LE, Pascual U, Hodgkin T (2007) Utilizing and conserving agrobiodiversity in agricultural
816 landscapes. *Agric Ecosyst Environ* 121(3):196–210

817 Jackson LE, Pulleman MM, Brussaard L et al. (2012) Social-ecological and regional adaptation of
818 agrobiodiversity management across a global set of research regions. *Glob Environ Change* 22(3):623–
819 639

820 Janssen MA, Bodin Ö, Anderies JM, Elmqvist T, Ernstson H, Mcallister RRJ, Olsson P, Ryan P (2006).
821 Toward a Network Perspective of the Study of Resilience in Social-Ecological Systems. *Ecol. Soc.*
822 11(1):15.

823 Jarvis DI, Brown AHD, Cuong PH et al. (2008) A global perspective of the richness and evenness of
824 traditional crop-variety diversity maintained by farming communities. *Proc Natl Acad Sci*
825 105(14):5326–5331

826 Kawa NC, McCarty C, Clement CR (2013) Manioc varietal diversity, social networks, and distribution
827 constraints in rural Amazonia. *Curr Anthropol* 54(6):764–770

828 Klerkx L, Aarts N, Leeuwis C (2010) Adaptive management in agricultural innovation systems: The
829 interactions between innovation networks and their environment. *Agric Syst* 103(1):390–400

830 Krishna A (2003) Partnerships between local governments and community-based organisations:
831 exploring the scope for synergy. *Public Adm Dev* 23(4):361–371

832 Labeyrie V, Thomas M, Muthamia ZK, Leclerc C (2016) Seed exchange networks, ethnicity, and
833 sorghum diversity. *Proc Natl Acad Sci* 113:98–106

834 Landis DA (2017) Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic*
835 *Appl Ecol* 18(1):1–12

836 Leclerc C, Coppens d’Eeckenbrugge G (2012) Social organization of crop genetic diversity. The G x E
837 x S interaction model. *Diversity* 4(1):1–32

838 Lescourret F, Magda D, Richard G, Adam-Blondon AF, Bardy M, Baudry J, Doussan J, Dumont B,
839 Lefèvre F, Litrico I (2015) A social–ecological approach to managing multiple agro-ecosystem services.
840 *Curr Opin Env Sustain* 14(1):68-75

841 Leventon J, Schaal T, Velten S, Dänhardt J, Fischer J, Abson DJ, and Newig J (2017) Collaboration or
842 fragmentation? Biodiversity management through the common agricultural policy. *Land Use Policy*
843 64(1): 1–12.

844 Lichtenberg E M, Kennedy C M, Kremen C et al. (2017) A global synthesis of the effects of diversified
845 farming systems on arthropod diversity within fields and across agricultural landscapes. *Glob Change*
846 *Biol* 23(11):4946-4957

847 Lin BB (2011) Resilience in agriculture through crop diversification: adaptive management for
848 environmental change. *BioScience* 61(3):183–193

849 Lippe M, Bithell M, Gotts N, Natalini D, Barbrook-Johnson P, Giupponi C, Hallier M, Hofstede GJ, Le
850 Page C, Matthews RB, Schlüter M, Smith P, Teglio A, Thellmann K (2019) Using Agent-based
851 modelling to simulate Social-Ecological Systems across scales. *GeoInformatica* 23(2):269-298.
852 doi:10.1007/s10707-018-00337-8

853 Lowder SK, Scoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms,
854 and family farms worldwide. *World Dev* 87(1): 16–29

855 McGuire S, Sperling L (2013) Making seed systems more resilient to stress. *Glob Environ Change*
856 23(3):644–653. doi:10.1016/j.gloenvcha.2013.02.001

857 McGuire S, Sperling L (2016) Seed systems smallholder farmers use. *Food Secur* 8(1):179–195

858 Mijatović D, Van Oudenhoven F, Eyzaguirre P, Hodgkin T (2013) The role of agricultural biodiversity
859 in strengthening resilience to climate change: towards an analytical framework. *Int J Agric Sustain*
860 11(2):95–107

861 Morrison TH, Adger WN, Brown K, Lemos MC, Huitema D, Phelps J, Evans L, Quinn (2019) The
862 Black Box of Power in Polycentric Environmental Governance. *Glob Envl Change* 57(1):101934.

863 Mwongera C, Boyard-Micheau J, Baron C, Leclerc C (2014) Social Process of Adaptation to
864 Environmental Changes: How Eastern African Societies Intervene between Crops and Climate. *Weather*
865 *Clim Soc* 6 (3):341-356. doi:10.1175/WCAS-D-13-00034.1

866 Olsson P, Folke C, Berkes F (2004) Adaptive comanagement for building resilience in social–ecological
867 systems. *Environ Manage* 34(1):75–91

868 Padmanabhan MA (2008) Collective action in agrobiodiversity management: gendered rules of
869 reputation, trust and reciprocity in Kerala, India. *J Int Dev* 20(1):83-97

870 Pautasso M, Aistara G, Barnaud A, et al. (2013) Seed exchange networks for agrobiodiversity
871 conservation. A review. *Agron Sustain Dev* 33(1):151–175. doi:10.1007/s13593-012-0089-6

872 Porcuna-Ferrer A, Fiala V, Freyer B, van Etten J, Vernooij R, Probst L (2020) Do community seed banks
873 contribute to the social-ecological resilience of communities? A case-study from Western Guatemala.
874 *Intl J Agr Sustain* 18(3): 232-249.

875 Pressoir G, Berthaud J (2004) Population structure and strong divergent selection shape phenotypic
876 diversification in maize landraces. *Heredity* 92(2): 95-101

877 Qualset CA, McGuire PE, Warburton ML (1995) In California: 'Agrobiodiversity' key to agricultural
878 productivity. *Calif Agric* 49 (6):45–49. doi:10.3733/ca.v049n06p45

879 Rathwell KJ, Peterson GD (2012) Connecting social networks with ecosystem services for watershed
880 governance: a social ecological network perspective highlights the critical role of bridging
881 organizations. *Ecol Soc* 17(2):24. doi:10.5751/ES-04810-170224

882 Reed M, Evely AC, Cundill G, Fazey IRA, Glass J, Laing A, Newig J, Parrish B, Prell C, Raymond C
883 (2010) What is social learning? *Ecol Soc* 15 (4):r1

884 Remans R, Wood SA, Saha N, Anderman TL, DeFries RS (2014) Measuring nutritional diversity of
885 national food supplies. *Glob Food Secur* 3(3-4):174–182

886 Renard D, Tilman D (2019) National food production stabilized by crop diversity. *Nature*
887 571(7764):257–260

888 Ricciardi V (2015) Social seed networks: identifying central farmers for equitable seed access. *Agric*
889 *Syst*139(1):110-121

890 Ricciardi V, Ramankutty N, Mehrabi Z, Jarvis L, Chookolingo B (2018) How much of the world's food
891 do smallholders produce? *Glob Food Secur* 17(1):64–72

892 Rockenbach T, Sakdapolrak P (2017) Social networks and the resilience of rural communities in the
893 Global South: a critical review and conceptual reflections. *Ecol Soc* 22(1):10. doi:10.5751/ES-09009-
894 220110

895 Rosset PM, Machín Sosa B, Roque Jaime AM, Ávila Lozano D R (2011). The Campesino-to-Campesino
896 agroecology movement of ANAP in Cuba: social process methodology in the construction of sustainable
897 peasant agriculture and food sovereignty. *J Peasant Stud* 38(1): 161-191

898 Roux X, Barbault R, Baudry J, Burel F, Doussan I, Garnier E, Herzog F, Lavorel S, Lifran R, Roger-
899 Estrade J, Sarthou J-P, Trommetter M (2009). *Agriculture and biodiversity: promoting synergies*. INRA.
900 Paris

901 Salliou N, Barnaud C (2017) Landscape and biodiversity as new resources for agro-ecology? Insights
902 from farmers' perspectives. *Ecol Soc* 22(2):16. doi:10.5751/ES-09249-220216

903 Sayles JS, Baggio JA (2017) Social–ecological network analysis of scale mismatches in estuary
904 watershed restoration. *Proc Natl Acad Sci* 114(10):E1776–E1785. doi:10.1073/pnas.1604405114

905 Sperling L, Cooper HD, Remington T (2008) Moving towards more effective seed aid. *The J of Dev*
906 *Studies* 44(4): 586-612

907 Steingröver EG, Geertsema W, van Wingerden WK (2010) Designing agricultural landscapes for natural
908 pest control: a transdisciplinary approach in the Hoeksche Waard (The Netherlands). *Landsc Ecol*
909 25(6):825–838

910 Stubbs M, Lemon M (2001) Learning to network and networking to learn: facilitating the process of
911 adaptive management in a local response to the UK's national air quality strategy. *Environ Manage*
912 27(3):321–334

913 Thomas M, Caillon S (2016) Effects of farmer social status and plant biocultural value on seed
914 circulation networks in Vanuatu. *Ecol Soc* 21(2):13. doi:10.5751/ES-08378-210213

915 Thomas M, Dawson JC, Goldringer I, Bonneuil C (2011) Seed exchanges, a key to analyze crop
916 diversity dynamics in farmer-led on-farm conservation. *Genet Resour Crop Evol* 58(3):321–338.
917 doi:10.1007/s10722-011-9662-0

918 Thomas M, Demeulenaere E, Dawson JC et al. (2012). On-farm dynamic management of genetic
919 diversity: the impact of seed diffusions and seed saving practices on a population-variety of bread wheat.
920 *Evol Appl* 5(8):779-795

921 Thomas M, Thépot S, Galic N, Jouanne-Pin S, Remoué C, Goldringer I (2015). Diversifying
922 mechanisms in the on-farm evolution of crop mixtures. *Mol Ecol* 24(12):2937-2954

923 Thrupp LA (2000) Linking Agricultural Biodiversity and Food Security: the Valuable Role of
924 Agrobiodiversity for Sustainable Agriculture. *Int Aff* 76(2):283–297

925 Tschardt T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J, Whitbread A
926 (2012) Global food security, biodiversity conservation and the future of agricultural intensification. *Biol*
927 *Conserv* 151(1):53–59

928 Valente TW (1996). Social network thresholds in the diffusion of innovations. *Soc Net* 18(1):69-89

- 929 van Bruggen A, Nikolic I, Kwakkel J (2019) Modeling with Stakeholders for Transformative Change.
930 Sustainability 11(3): 825
- 931 Vernooy, R., Shrestha, P., Sthapit, B. (Eds.). (2015). Community seed banks: Origins, evolution and
932 prospects. Routledge. New York.
- 933 Vialatte A, Barnaud C, Blanco J, et al. (2019) A Conceptual Framework for the Governance of Multiple
934 Ecosystem Services in Agricultural Landscapes. *Landsc Ecol* 34 (7):1653-1673.
935 <https://doi.org/10.1007/s10980-019-00829-4>.
- 936 Voinov A, Bousquet F (2010). Modelling with stakeholders. *Env Model Soft* 25(11):1268-1281.
- 937 Waha K, van Wijk MT, Fritz S, See L, Thornton PK, Wichern J, Herrero M (2018) Agricultural
938 diversification as an important strategy for achieving food security in Africa. *Glob Change Biol*
939 24(8):3390–3400. doi:10.1111/gcb.14158
- 940 Wasserman S, Faust K (1994) Social network analysis: Methods and applications. Cambridge university
941 press, Cambridge