



**HAL**  
open science

## Linking seed networks and crop diversity contributions to people: A case study in small-scale farming systems in Sahelian Senegal

Vanesse Labeyrie, Rachel Friedman, Sophie Donnet, Océane Cobelli, Ndeye Fatou Faye, Jacopo Baggio, María Felipe-Lucia, Christine Raimond

### ► To cite this version:

Vanesse Labeyrie, Rachel Friedman, Sophie Donnet, Océane Cobelli, Ndeye Fatou Faye, et al.. Linking seed networks and crop diversity contributions to people: A case study in small-scale farming systems in Sahelian Senegal. *Agricultural Systems*, 2023, 211, pp.103726. 10.1016/j.agsy.2023.103726 . hal-04308463

**HAL Id: hal-04308463**

**<https://hal.science/hal-04308463>**

Submitted on 3 Jun 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Linking seed networks and crop diversity contributions to people: a case study in small-scale farming systems in Sahelian Senegal

Labeyrie V., Friedman R.S, Donnet S., Faye N.F., Cobelli O., Baggio J., Felipe-Lucia M.R., Raimond C., 2023. Linking seed networks and crop diversity contributions to people: a case study in small-scale farming systems in Sahelian Senegal. *Agricultural system*, vol. 2011, <https://doi.org/10.1016/j.agsy.2023.103726>

### Authors:

Vanesse Labeyrie<sup>1</sup>, Rachel S. Friedman<sup>2</sup>, Sophie Donnet<sup>3</sup>, Ndeye Fatou Faye<sup>4</sup>, Océane Cobelli<sup>1</sup>, Jacopo Baggio<sup>5</sup>, María R. Felipe-Lucia<sup>6</sup>, Christine Raimond<sup>7</sup>.

<sup>1a</sup>CIRAD, UMR SENS, F-34398, Montpellier, France; <sup>1b</sup>SENS, Univ Montpellier, CIRAD, IRD, UPVM, Montpellier, France

<sup>2</sup> Australian National University, Institute for Climate, Energy & Disaster Solutions, Acton, Australia

<sup>3</sup> Université Paris-Saclay, AgroParisTech, INRAE, UMR MIA Paris-Saclay, 91120, Palaiseau, France

<sup>4</sup> ISRA, BAME, Dakar, Senegal

<sup>5a</sup> UCF, School of Politics, Security and International Affairs., Orlando, Florida; <sup>5b</sup> Sustainable Coastal Systems Cluster, UCF

<sup>6</sup> Department of Ecosystem Services, Helmholtz Centre for Environmental Research - UFZ, Leipzig, Germany / German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Germany

<sup>7</sup> CNRS, UMR PRODIG, Paris, France.

### Abstract

Small farms rely on a range of nature's contributions to people (NCPs) provided by crop diversity, covering both material and immaterial dimensions that are crucial for livelihoods and well-being. The maintenance of these NCPs over time, despite perturbations, is a key component of small farms' resilience. However, the processes involved in the access of farmers to the different NCPs provided by crops are largely unknown. Such knowledge would be instrumental for evaluating the vulnerability or resilience of farmers to potential disruptions to access channels. In this study, we analyzed how the seed provisioning networks used by farmers to access crops relate to the different NCPs they receive from these crops, through a case study in Sahelian Senegal. Field surveys were conducted with 91 farmers, half men and half women, belonging to 49 households from two villages. The surveys documented which varieties of three important staple crop species (pearl millet, cowpea, peanut) farmers grew. Farmers were asked to cite their motivations for cultivating each variety as a proxy for NCPs, and to explain from where they obtained the seeds of each variety of these three species. We mobilized recent developments in Social-Ecological Network research, representing the relationships between social entities (i.e., farmers and seed sources), ecological entities (i.e., crops), and NCPs (i.e., motivations) as networks. We applied a block model clustering approach to analyze these relationships by testing if particular seed sources were associated with particular motivations, and if differences existed between men and women. We also analyzed households' profiles according to the motivations they cited and the seed sources they were connected to. Finally, we discuss how the observed social-ecological network patterns affect the access of men and women farmers to NCPs, and their consequences for the maintenance of NCP provision in the face of perturbations.

## 1           **Introduction**

2  
3 Small farms, cultivating less than 5 hectares each, produce an estimated 50% of the food  
4 calories globally (Ricciardi et al. 2018). These small farms are mostly located in Africa, South  
5 and East Asia, and Latin America and face a variety of factors that make them vulnerable to  
6 multiple types of socio-environmental shocks. Fast changing climatic, biophysical, economic,  
7 social and political conditions affect small farms, and their lack of economic and physical assets  
8 make them particularly vulnerable to these changes that threaten their livelihood (Morton,  
9 2007).

10  
11 Crop diversity ensures the provision of multiple benefits related to nature’s contributions to  
12 people (NCPs), such as food and fiber, medicinal and ornamental plants, identity and cultural  
13 values, soil fertility and reduction of soil erosion (Demongeot, Chaplin-Krammer, & Pascual,  
14 2022; Díaz et al. 2018). Furthermore, crop diversification has been identified as a key factor for  
15 the resilience of smallholder farming systems—the capacity of these systems to respond and  
16 adapt to the range of perturbations they face through the maintenance of NCPs that are  
17 instrumental to system function (Renard and Tilman, 2021, Cabell and Oelofse 2012, Kremen  
18 and Merenlender 2018, Schipanski, et al. 2016). Currently smallholder farms grow a much  
19 greater diversity of crop species and varieties than larger farms (Ricciardi et al. 2018), but a  
20 tendency toward uniformization of crops at the global scale has been observed (Khoury et al.  
21 2014; Martin et al. 2019). Smallholders’ ability to diversify their crops is a key factor affecting  
22 agroecosystem resilience, as well as for facilitating the transition toward more sustainable forms  
23 of agriculture (Altieri and Nicholls, 2017; Jackson et al. 2010).

24  
25 Crop diversity is clearly linked to the ability of small farms to access a range of different seed  
26 varieties. Small farms access seeds for different crops through numerous channels (McGuire  
27 and Sperling, 2016). Although smallholder farmers often rely on barter or exchange with peers  
28 or monetized transactions at local markets and shops to get seeds, they tend to mobilize a wide  
29 range of other seed sources such as NGOs, private seed companies, and government programs  
30 (Almekinders and Louwaars, 2002). A number of studies have examined seed circulation  
31 networks in smallholder communities in various contexts, and this literature shows that  
32 modalities of seed sourcing can vary strongly across sites (e.g. Delaquis, et al. 2018; Tadesse,  
33 et al. 2017), even within the same country (Cobelli et al. In Press). Recent studies indicate that  
34 farmers’ seed sourcing practices are related to a range of NCPs (Urrea-Hernandez,

35 Almekinders, Van Dam 2016, Kilwinger 2020); however, quantitative studies on this topic are  
36 lacking despite the importance of this relationship for household resilience.

37

38 Seed distribution and exchange channels influence the types of crops that farmers access  
39 (Louwaars & Manicad, 2022), therefore impacting the types of NCPs farmers receive. Studies  
40 in parts of Africa have highlighted how local seed networks and national seed distribution  
41 channels allow farmers to access a variety of types of crops with different functions (McGuire  
42 and Sperling, 2013, 2016). For instance, some crop species and landraces—local crop varieties  
43 that have been reproduced over several generations by farmers in a given location—can be  
44 accessed by farmers only through local networks, because they are not distributed through  
45 official channels. This has been observed for indigenous vegetables that have important  
46 nutritional properties and are adapted to local conditions (Croft, et al. 2017), and for cereal  
47 landraces culturally valued locally (Labeyrie et al. 2014). On the other hand, the seed  
48 dissemination channels of private seed companies or state extension services allow farmers to  
49 access varieties resulting from targeted breeding efforts with productivity advantages such as a  
50 short growth cycle duration or a high yield in favorable growing conditions. Despite the  
51 importance of combining official seed distribution channels with farmers' seed networks to  
52 enhance the resilience of small farms (McGuire and Sperling, 2013, 2016), relatively little is  
53 known about how seed sourcing practices relate to the NCPs that farmers obtain from crops.

54

55 Representing the complex interactions between a range of social and ecological/biophysical  
56 entities as social-ecological networks (SENs) is increasingly proposed for understanding the  
57 processes involved in NCP provision (Felipe-Lucia, et al. 2022, Dee et al. 2017). SENs provide  
58 a conceptual framework for analyzing the interactions and relationships between smallholder  
59 seed sourcing networks and the NCPs associated with crops. Network approaches conceptualize  
60 a system as a set of nodes (vertices) and the relationships that exist between them (ties or edges),  
61 and can be used to analyze complex social–ecological interdependencies (Bodin et al. 2019).  
62 In these social-ecological networks, NCPs can be represented as nodes, edges between social  
63 and ecological nodes, attributes of nodes, or as emergent properties of the overall social-  
64 ecological network (Felipe-Lucia, et al. 2022, Dee et al. 2017, Bodin, et al. 2019, Sayles et al.  
65 2019). Dedicated network analysis tools can then be applied to analyze these interactions and  
66 relationships.

67

68 Here we mobilize these recent developments in SEN research to conceptualize and examine  
69 how farmers access different NCPs through the seed sourcing channels of various crop varieties,  
70 through a case study in Sahelian Senegal. Via interviews and surveys, we first identified the  
71 main seed sources for farmers in the area (i.e. inherited seeds, acquired via peers, local markets,  
72 etc.), and then we assessed the main motivations for growing the different chosen seed varieties.  
73 These motivations were used as proxies for NCPs and categorized as regulating, material, or  
74 non-material benefits according to the NCP framework (Pascual et al. 2017; Díaz et al. 2018).  
75 Then, we tested if particular seed sources were associated with particular motivations and if  
76 differences existed between men and women, and between households. Considering the  
77 strength of networks in capturing the interrelations and interdependencies between variables of  
78 interest, employing a SEN framing supports this study's aim to analyze the relationships  
79 between seed sources, seed varieties, and NCPs. In addition, the statistical analysis tools  
80 developed for network analysis allow dealing with the non-independence of observations,  
81 which is not possible with classical statistical methods. In the next sections, we detail the  
82 methods to collect and analyze the network data, and then report on the results. Finally, we  
83 discuss how the observed SEN patterns affect the access of men and women farmers to crop  
84 diversity, and consider the associated consequences for the maintenance of NCP provisioning  
85 in the face of shocks to the agricultural system for both gender groups.

86

## 87 **Methods**

88

### 89 **Study site**

90 The study site covered two neighboring villages located in the central western part of the  
91 groundnut basin (old basin), in the Department of Fatick, Senegal (Figure 1). These two villages  
92 are located in the same biophysical and socioeconomic context, within the area covered by the  
93 Niakhar Health and Demographic Surveillance System piloted by the French National Research  
94 Institute for Sustainable Development (IRD), located 135 km east of the capital city, Dakar  
95 (Delaunay et al. 2013). The climate is Sudano-Sahelian, with a short rainy season from  
96 June/July to October and a long dry season of eight to nine months. Annual rainfall is highly  
97 variable, but the average rainfall has been 502 mm/year since 2000 (Sultan et al. 2015).

98

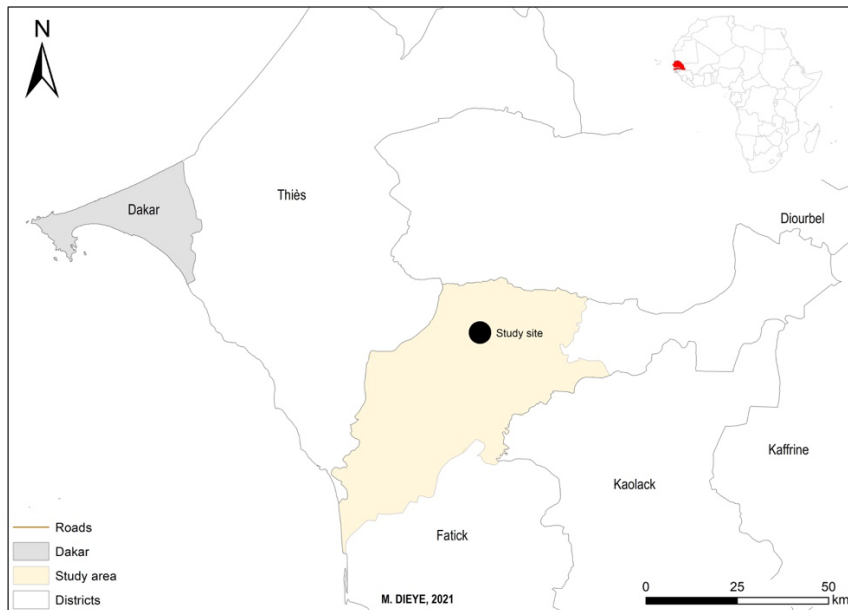
99 The Sereer farmers, who make up nearly 97% of the inhabitants living in this area, are agro-  
100 pastoralists (Delaunay et al. 2013). They grow both cereals, mainly pearl millet (*Pennisetum*  
101 *glaucum*), and legumes, mainly cowpea (*Vigna unguiculata*) and groundnut (*Arachis*

102 *hypogaeae*), for self-consumption, animal feed, and for local sale. These crops are grown either  
103 in association or in rotation on sandy soils in agroforestry systems with *Faidherbia* trees. Plots  
104 are usually delineated with roselle (*Hibiscus sabdariffa*) hedgerows, the flowers of which are  
105 sold by women at local markets. Fallow is rare, as land is fully occupied in the area due to a  
106 rapid population and urbanisation growth since the end of the twentieth century. A few  
107 vegetables are also grown near the house for preparing sauces, such as okra (*Abelmoschus*  
108 *esculentus*) and *cucurbitaceae*. A range of commercial farming activities, such as watermelon  
109 cultivation or cattle raising for meat, are developing in the area. Farmers in surveyed villages  
110 have limited access to chemical inputs, and they only rely on animal-driven tools for plowing,  
111 sowing, and harvesting. Irrigation is also not possible in the area due to groundwater salinity.  
112 A recent study details the patterns of crop diversity and its management practices in the two  
113 studied villages (Cobelli et al. In Press), indicating that farmers grow an average of 6 species,  
114 and between 1 and 2 varieties for the three species targeted in this study. Seed lots from different  
115 origins can be sown for a given variety within a household (i.e. multiple seed sources).

116

117 Households are organized into concessions, which group together members of the same family  
118 and vary in size. One or more households (elementary families) live in the same concession and  
119 share the land to be cultivated. Each household represents a family unit composed of the sons  
120 or brothers of the head of the concession, their wives, children, and uterine nephews. The land  
121 in the concession is divided among the different heads of households, each of whom is  
122 responsible for the self-sufficiency of his or her household (Benoit-Cattin & Faye, 1982;  
123 Guigou, 1992). These heads are the ones who determine the allocation of plots, the cropping  
124 calendar, the quantities sown, and the distribution of family labor.

125



126

127 *Figure 1. Study site location*

128

129 **Ethics approval**

130 To carry out the study, the Code of Ethics of the International Society of Ethnobiology (ISE)  
 131 was followed. The work was conducted in collaboration with the Senegalese Institute for  
 132 Agricultural Research (ISRA). Before conducting individual surveys, a meeting was organized  
 133 with the leader of the village to fully inform them of the purpose of the research and how it  
 134 would be conducted and to seek their consent. The methodology and the type of data collected  
 135 were explained to farmers prior to the interviews to inform them about the implications of their  
 136 participation in the surveys. The future use of the data and the expected benefits of the study  
 137 were described and discussed with the interviewees. The farmers participated voluntarily and  
 138 free from coercion, and they had the right to withdraw at any time. Before conducting the  
 139 interviews, farmers gave their prior informed consent verbally. No activities were conducted  
 140 without such consent. The involvement of an interpreter, a native of the study area, helped  
 141 ensure that local rules and customs, as well as the rights and well-being of the farmers  
 142 interviewed, were respected.

143

144 **Data collection**

145 Surveys were conducted between March and June 2018 in the two selected villages. The first  
 146 part of the study aimed to obtain general information about the agrarian context of each village  
 147 through semi-structured interviews with each village leader. We also carried out a census of  
 148 households in each village and with the village leader, and established a typology of households

149 according to their economic status based on key descriptors (total area cultivated, farm  
150 equipment, availability of labor, working animals). This typology led to the construction of  
151 three classes (rich, middle-income, poor). We selected a stratified random sample of three low  
152 income households, four middle-income, and three rich households. We then employed  
153 snowball sampling and conducted surveys with all the households cited as seed providers by  
154 the heads of these 10 households. Snowball sampling is appropriate given the cultural context,  
155 where personal introductions and referrals are key in order to elicit responses. Further, albeit  
156 non-random, snowball sampling is often the method of choice when eliciting social network  
157 data (Carrington, Scott and Wasserman 2005), which was the initial purpose of the project in  
158 which this study takes place.

159 We surveyed a total of 49 households for the farm survey. In each household, we interviewed  
160 separately both male and female household heads, as the people responsible for selecting and  
161 managing crop seeds. We interviewed a total of 85 people (43 men and 42 women) as in some  
162 households there were single household heads or one of the heads could not be interviewed.  
163 This represents about 80% of the number of households in the two study villages. One of the  
164 co-authors (OC) interviewed each household head once individually, with the aid of a local  
165 translator who was intensively trained for this type of survey and had experience working for  
166 researchers within the Niakhar Health and Demographic Surveillance System.

167  
168 The survey included four sections that applied to both male and female household heads on  
169 each farm. The first part of the survey aimed at collecting socio-economic and demographic  
170 information concerning the household and both household heads. The second part of the survey  
171 was an inventory of crop species and varieties of millet, groundnut, and cowpea cultivated on  
172 the farm in 2017. We selected these three crop species, because they are the main staple crops  
173 grown in the area and have different functions for households. The inventory of crop varieties  
174 was based on the names cited by the respondents, which reflect how farmers manage their  
175 genetic resources (Berg, 2009). Collective discussions at each site helped to identify possible  
176 synonyms (same biological object associated with different names) and to homogenize the  
177 names of varieties. This inventory therefore does not reflect the varietal diversity characterized  
178 by genetic markers, but rather that identified and named by farmers. The third part of the survey  
179 aimed at documenting seed sources mobilized by farmers, asking where farmers obtained the  
180 seeds of each variety of the three selected species cultivated in 2017 during their last and most  
181 recent seed sourcing event outside of the farm (i.e. external sourcing that could have occurred  
182 prior to 2017). Seed sourcing event is the instance of the seed of one variety sourced by a farm



183 and coming from one source. Self-sourcing events were excluded as we were interested only in  
 184 external sourcing. This allowed us to document the origin of the current seed lots cultivated on  
 185 the farms, prior to any further on-farm reproduction, if relevant. The last seed sourcing event  
 186 was chosen, because previous studies have linked the overall level of crop diversity on-farm to  
 187 the diversity of the last seed sourcing events (e.g. Calvet-Mir 2012). The modes of seed supply  
 188 were grouped into 5 main categories (Table 1.a).

189  
 190 The last part of the survey aimed to document the NCPs farmers get from each variety of the  
 191 three selected crop species. As a proxy for NCPs, we used the motivations farmers reported for  
 192 cultivating each variety of the three selected species by asking the question “Why do you grow  
 193 this specific variety?”. The motivations were collected from farmers through an open-ended  
 194 individual survey. This free elicitation procedure was found to give a better account of what  
 195 objects are perceived to be doing or providing for the users (Steenkamp and Van Trijp 1997).  
 196 Farmers could cite as many motivations as they wanted for each variety. The researcher and  
 197 translator conducting the survey were trained to ask the farmer to provide details about these  
 198 motivations to make sure that farmers’ ideas were adequately captured. These motivations were  
 199 coded *a posteriori* into seven categories, with a total of 11 sub-categories (Table 1.b). This part  
 200 of the survey was conducted separately with men and women for all the varieties of the three  
 201 target species cultivated by each household.

202  
 203 *Table 1. Categories of seed sources and of motivations used for the study.*

<b>a. Seed Sources</b>	<b>Details</b>	<b>Type of seed</b>
1. Legacy	Farmers inherited the seeds from their parents	Farmers’ seeds (i.e. multiplied on-farm), mainly from landraces but also from creolized varieties
2. Interpersonal	Farmers get seeds from peers, mainly through gifts or exchanges, and more rarely with money	Mainly farmers’ seeds, either from landraces or creolized varieties
3. Local markets and seed sellers	Farmers bought seeds at local markets from other farmers or from brokers, or they bought seeds in local shops	Mainly farmers’ seeds, either from landraces or creolized varieties
4. Rural development organizations	Farmers get seeds from NGOs, cooperatives, associations, or extension services and research centers	Mainly certified seeds from varieties bred by national research centers or private companies

5. Agrodealers and others sources	Farmers get seeds from other sources, mainly agrodealers	Mainly certified seeds
<b>b. Nature Contributions to People (NCP)</b>	<b>Motivations</b>	<b>Exemples</b>
<b>Regulation NCP</b>		
1. Agronomic	1.1. Crop variety well adapted to the local climate	Drought resistant
	1.2. Crop variety with adapted growth cycle length	Short or long growth cycle
	1.3. Crop variety presenting other agronomic characteristics of interest	Adapted to local soils, low fertility requirement, easy to grow, resistant to birds
<b>Material NCP</b>		
2. Production	2.1. Crop variety that provides a good production in quantity, and all the year long	
	2.2. Crop variety that provides a good production of processed products, and good quality products	Good flour/oil production, big seeds / pods
Food preparation and consumption	3.1. Crop variety that provides tasty and nutritive food, adapted to the different specific food uses	Staple food, food for shortage periods, food diversification, Tasty food production, with a nice texture, nutritional qualities, specific culinary use
	3.2. Crop variety that limits workload for food preparation	Easy to cook or mash
Sale	4.1. Crop variety that provides marketable products	High price on the local market, source of income for women
Other uses	5.1. Crop variety that provides other products for non-food uses	Fodder, building material
<b>Non-material NCP</b>		
Attachment	6.1. Crop varieties that makes farmers remember their father, and is part of their attachment to tradition	Father memory, attachment to tradition,

Familiarity	7.1. Crop varieties that farmers know well, and that can be easily accessed because they are available locally.	Deep knowledge of the variety, variety which seeds are available in the household, variety grown by everybody in the village
-------------	---	--

204

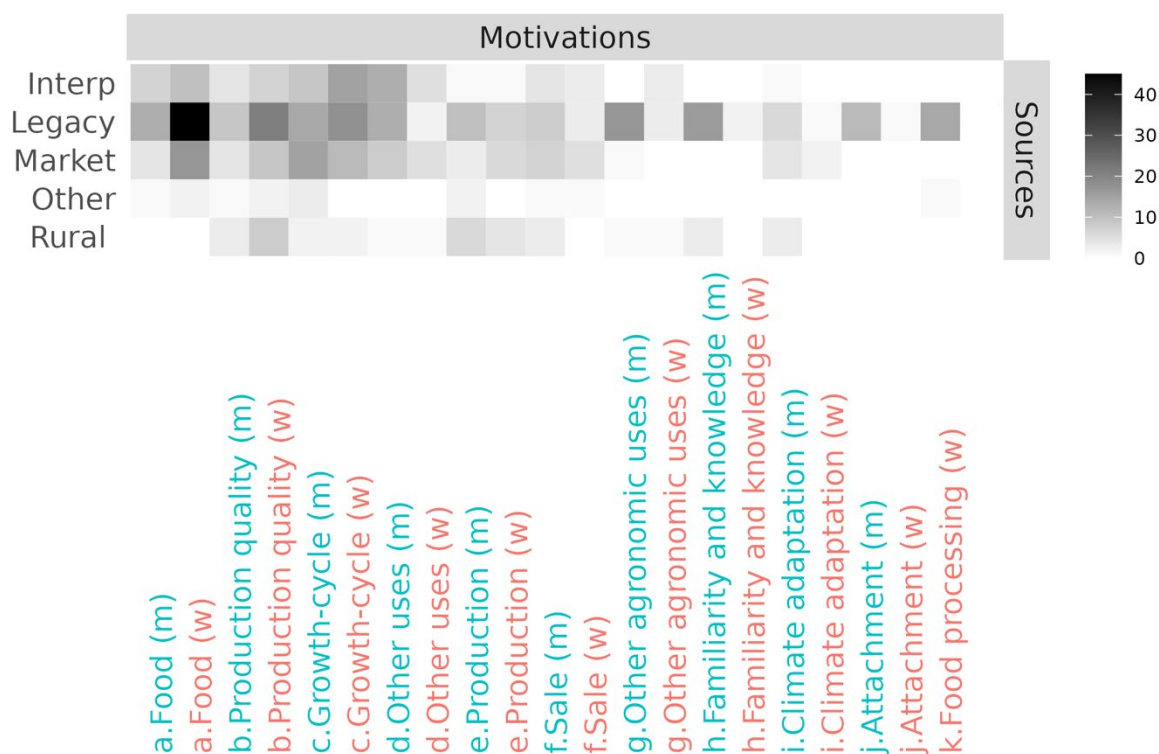
205 **2.4 Data analysis**

206

207 We first used descriptive analysis to summarize the frequency of the different varieties of each  
 208 crop species. Then, we conceptualized the relationship between crop varieties, seed sources,  
 209 and motivations (as a proxy for NCPs) as social-ecological networks (Felipe-Lucia, et al. 2022).  
 210 Depending on the analysis conducted to address the different research questions listed bellow,  
 211 nodes represented the individual households, seed sources, crop varieties, or  
 212 motivations/benefits associated with them. Ties represented various types of relationships  
 213 between the nodes. We constructed three networks described below, involving two or three  
 214 types of nodes, resulting in bipartite or tripartite networks. The three networks were analyzed  
 215 using a probabilistic model-based approach (namely latent block models and extensions)  
 216 described hereafter.

217 The three socio-ecological networks of interest were:

218 (i) **Network 1: sources x motivations.** First, we aimed to identify the most frequently cited seed  
 219 sources and motivations, and whether there were particular associations between the  
 220 motivations and the seed sources, when considering all the varieties together for all the three  
 221 species. Conducting an analysis for the three main crop species cultivated by farmers makes  
 222 sense, because farmers manage them together due to their complementary and sometimes  
 223 redundant functions in the farming system. We analyzed the “sources x motivations” weighted  
 224 bipartite network where two different types of nodes represented the different sources and  
 225 motivations, respectively, and where the ties represented the number of times farmers cited a  
 226 given motivation for growing any variety that was obtained through a given seed source. Such  
 227 a bipartite network can be represented as a table (Figure 2), where the rows represent a given  
 228 type of nodes (e.g. sources), the columns represent another type of node (motivations), and at  
 229 row *i* and column *j* of the table one reads the number of times the source *i* has been cited for  
 230 motivation *j* (for instance, represented as a grey level). This representation is quite convenient  
 231 when considering small weighted networks.

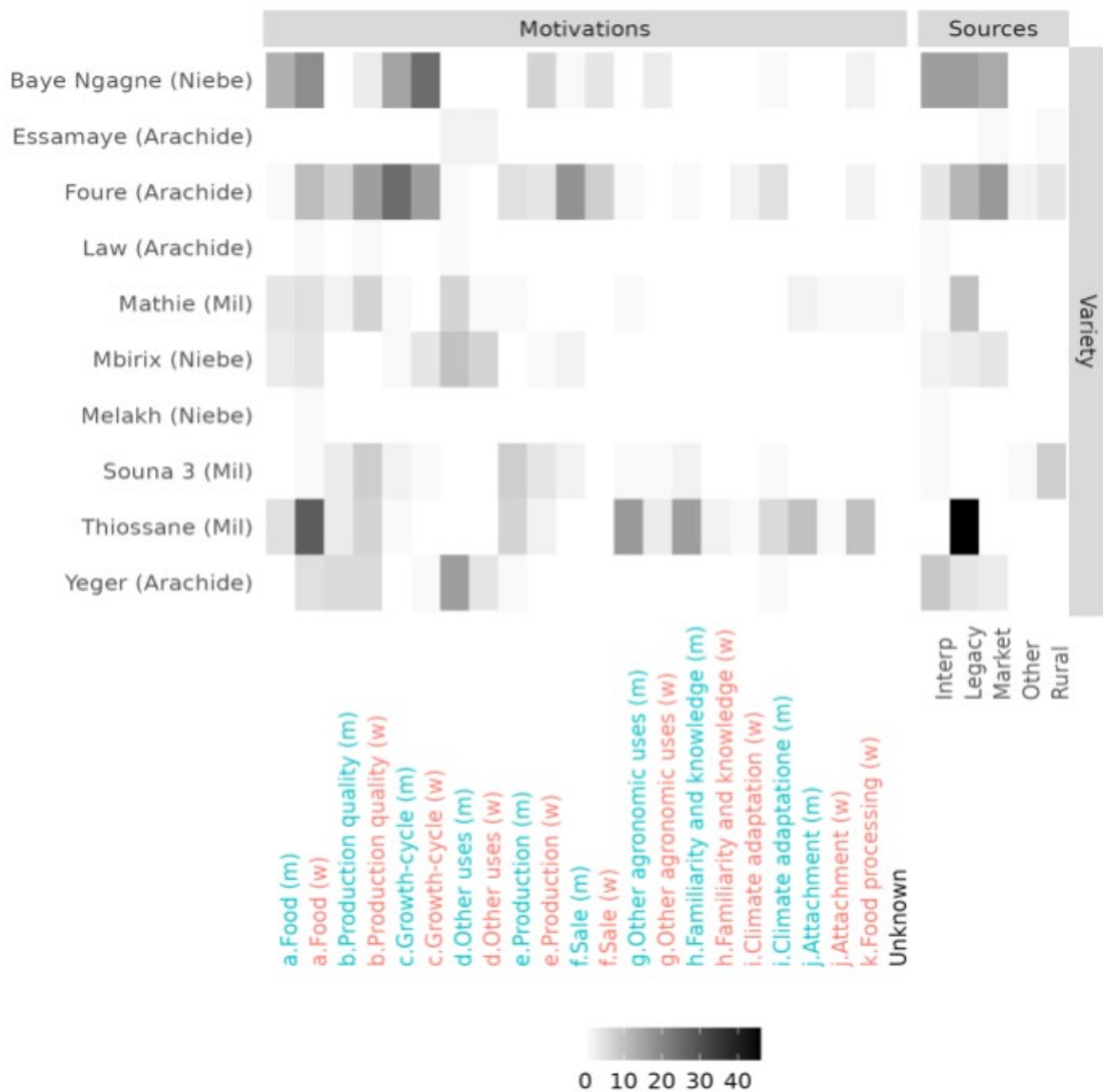


232

233 *Figure 2. Weighted bipartite network [Source x Motivations] on all species. Represented as a*  
 234 *table. Motivations cited by women are in red while the ones cited by men are in blue. The*  
 235 *darker the box (i,j) the more the source of supply is associated with motivation j. As an*  
 236 *example, 40 women declared that they got their varieties used for food from inheritance.*

237

238 **(ii) Network 2: Varieties x [motivations, seed sources].** We aimed to identify if the seed sources  
 239 used by farmers and the associated motivations differed between varieties. This allowed us to  
 240 bring a finer-grain discussion of the specifics of each variety and its contribution to the general  
 241 aggregated pattern observed for the three crop species. This division according to varieties was  
 242 more relevant than according to species, because the different varieties for a given species can  
 243 be linked to very different NCPs. For instance, for both cowpea and peanut, some varieties are  
 244 dedicated to fodder and other to grain production. We analyzed the “varieties x [motivations,  
 245 seed sources]” tripartite network. The ties between sources and varieties represented the number  
 246 of times each variety was obtained by farmers from a given source, and the ties between  
 247 varieties and motivation represented the number of times farmers cited the different motivation  
 248 for each variety (Figure 3). This tripartite network is represented by two tables sharing the same  
 249 rows.



251

252 *Figure 3. Tripartite network Varieties x [motivations, seed sources] Motivations cited by*  
 253 *women are in red while the ones cited by men are in blue. The darker the box (i,j) the more*  
 254 *the source of supply is associated with motivation j. As an example, 28 women declared that*  
 255 *they used the variety of mil Thiossane for food. All the interviewed people declare that they*  
 256 *obtained Thiossane by legacy.*

257

258 **(iii) Network 3: Households x [motivations, seed sources].** In order to identify different  
 259 household profiles of combined seed sourcing and motivations, we analyzed the “household x  
 260 [motivation, seed sources]” weighted tripartite network. The ties between households and  
 261 motivations represented the number of times each motivation was cited by farmers in that  
 262 household, and the ties between household and seed sources represented the number of times

263 farmers reported getting seeds for these sources (See SI 1 for the network matrix graphical  
264 display).

265

### 266 **A probabilistic approach to analyze the networks.**

267 When analyzing a network, it is important to get a mesoscopic view of its structure (or  
268 topology), thus highlighting any patterns and/or identifying the role played by  
269 households/individuals, motivations and seed sources. The probabilistic approach assumes that  
270 the networks at stake are the realization of unspecified probabilistic distributions. Using the  
271 probabilistic framework ensures theoretical properties of the inferred quantities and thus on the  
272 resulting decisions. In this paper, we employed latent block modelling (LBM) adapted to  
273 bipartite networks and its extensions to tripartite weighted networks (and more complex  
274 networks) by Bar-Hen et al (2021).

275

276 Specifically, the LBM presented here assumes that the interactions (counts) are distributed  
277 according to a Poisson distribution. To model connectivity heterogeneity, we assume that the  
278 nodes belong to (unobserved) blocks and that the intensity of connection between pairs of nodes  
279 varies depending on the blocks they belong to. The inference of the parameters of the model  
280 results in a non-supervised clustering of the nodes, where the clusters gather nodes of the same  
281 nature based on connectivity patterns (e.g. households or motivations) assuming that similar  
282 connectivity patterns imply similar roles in the network they are involved in. For instance,  
283 applying LBM to the tripartite network Households x [motivations, seed sources] would group  
284 together households having the same connectivity behavior, i.e. connected to the same set of  
285 seed sources and motivations. Contrary to community detection or other network analysis tools,  
286 the block modeling is agnostic when it comes to seeking predefined type of structure (hubs,  
287 communities, or embeddedness). The clustering algorithm employed in LBM assess clusters  
288 based on observed connectivity patterns and uses maximum likelihood to determine whether or  
289 not two nodes belong to the same cluster.

290 The final number of clusters was chosen following the principle of parsimony. We resorted to  
291 a model selection criterion (namely ICL) that selected the model that best fit the data, but  
292 penalized for over-fitting and fuzzy clustering (essentially, favoring clear clustering). The  
293 method was applied using the R package 'sbm' (Chiquet, Donnet, and Barbillon 2021). More  
294 details on the statistical method we employed are provided in the supplemental methods (SI 2).

295

296

297 **3. Results**

298

299 **3.1. Motivation and seed sources according to gender**

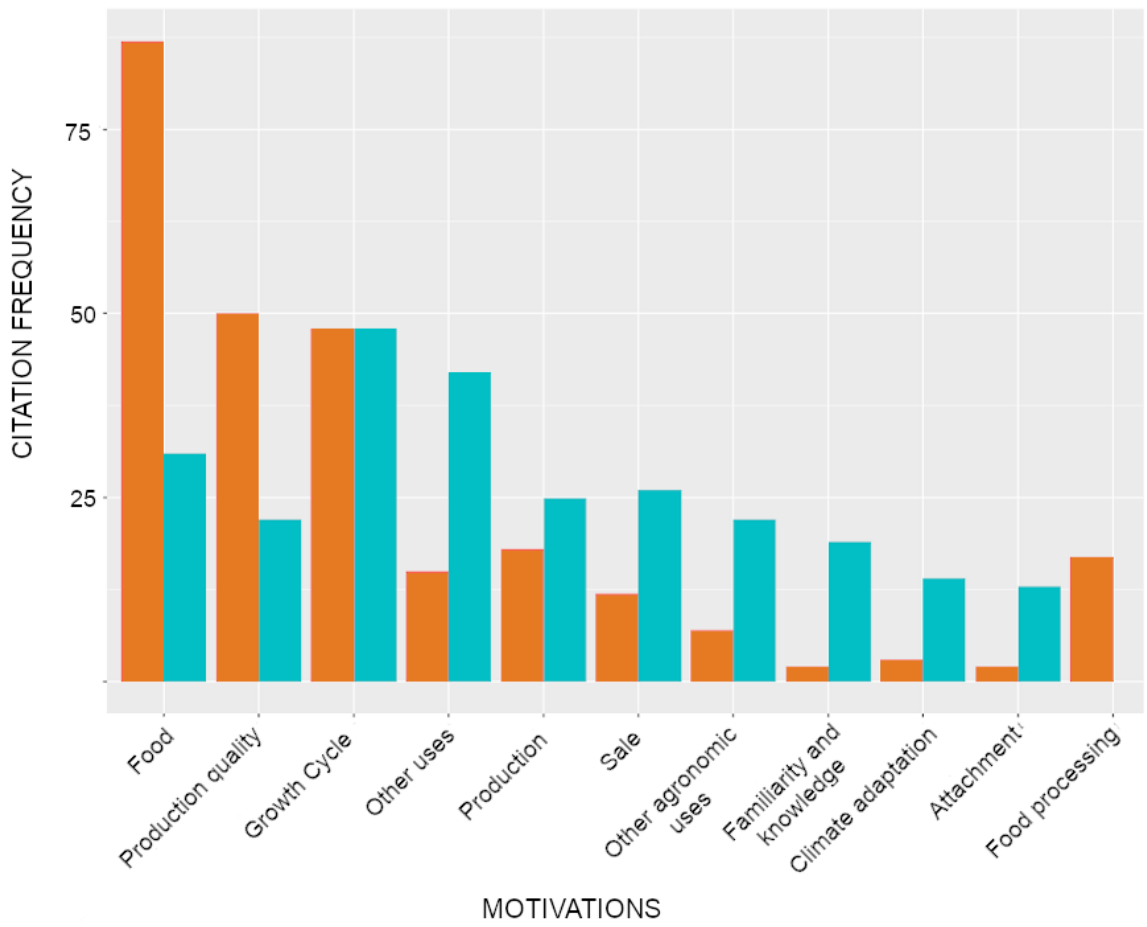
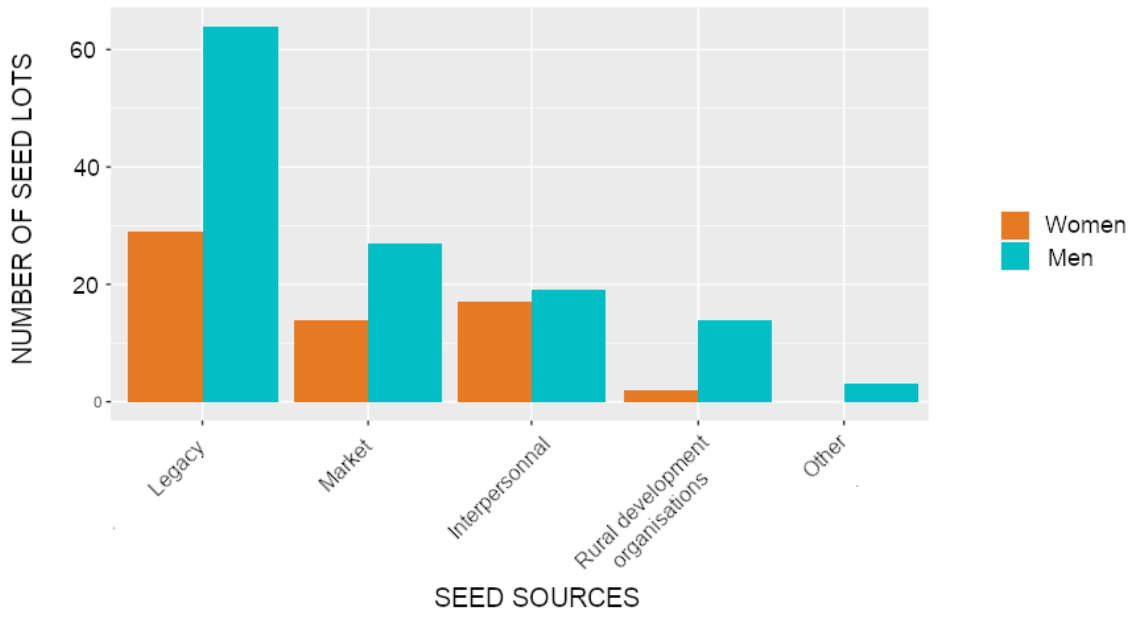
300

301 Overall, men reported sourcing seeds of the three target crop species twice as many times as  
302 women (127 seed sourcing events reported by men versus 62 reported by women). Farmers  
303 reported getting most of their seeds through legacy, interpersonal exchanges, and the market  
304 (Figure 4). Men obtained seeds more frequently through legacy than women, and this trend was  
305 observed to a lesser extent for market sourcing. Women more frequently obtained seeds through  
306 interpersonal exchanges. The rural development organizations were rarely cited as a source of  
307 seeds, and in most cases it was by men.

308

309 The most frequently cited motivations for cultivating the varieties differed between men and  
310 women. Women most frequently cited motivations related to food, such as the good taste and  
311 texture or nutritional properties, and then motivations related to the quality of production  
312 (mainly the quantity of flour or oil that the seed can produce) and to the growth cycle length.  
313 Men mainly cited motivations related to the growth-cycle length and to other uses, which  
314 mainly corresponded to fodder production. Motivations related to the familiarity of the seeds  
315 and to the knowledge and experience of how to grow them, to climate adaptation, and to  
316 attachment (e.g., identity and heritage value) were very rarely cited by women. Conversely,  
317 only women reported motivations related to food processing (i.e. easiness to cook and process  
318 the seeds).

319





322 *Figure 4. Top: Number of seed-lots obtained by men (n=127) and women (n=62) farmers*  
323 *from the five categories of seed sources. Bottom: number of citations per category of*  
324 *motivation by women (N=47) and men (N=44).*

325

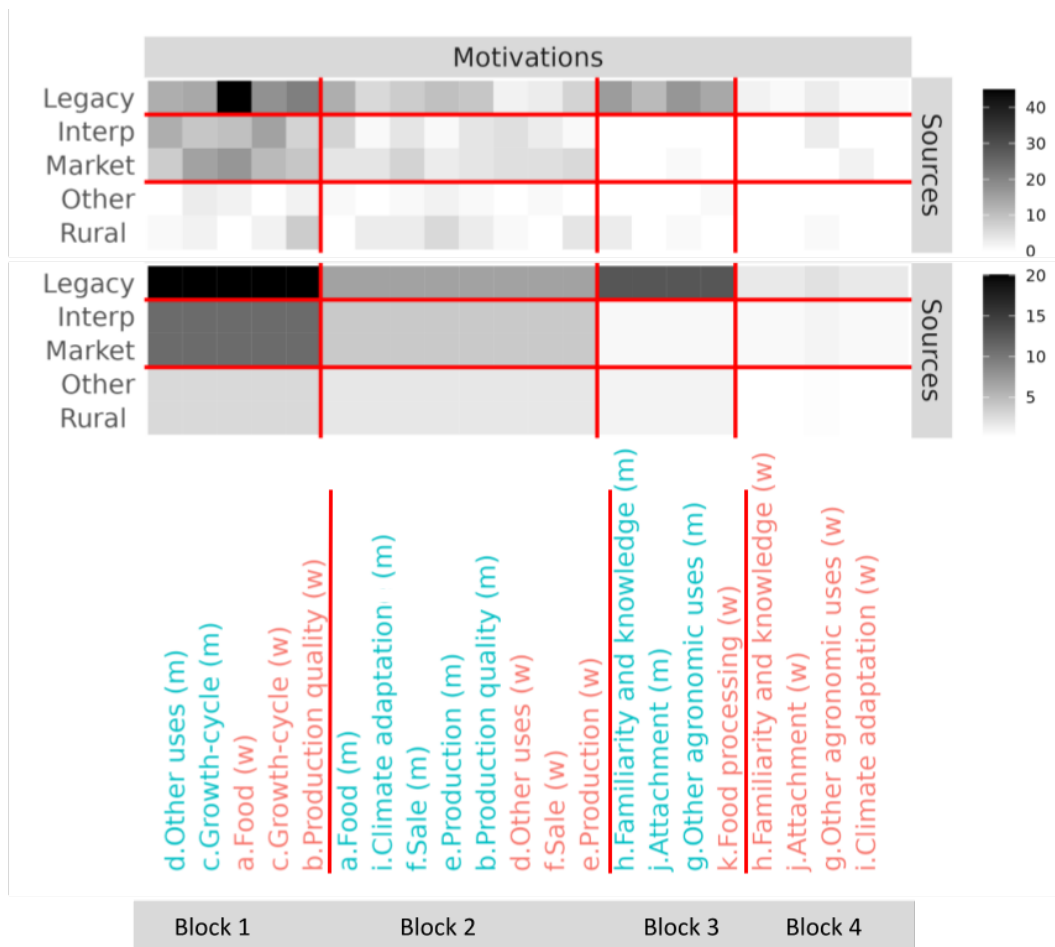
### 326 **3.2. Relationship between channels of seed sourcing and motivations**

327 The results of the LBM Model on the data aggregated for men and women and for the three  
328 species are represented in Figure 5. In Figure 5A, we reordered the rows and columns of the  
329 table with respect to the inferred blocks/clusters. We observed which associations of sources  
330 and motivation were more frequent than others. In order to highlight the differences between  
331 blocks, we plotted the estimated mean number of interactions between any pairs of row and  
332 column blocks (Figure 5B). The second representation gives a mesoscopic view of the table,  
333 ignoring the pair variability and focusing on the patterns.

334

335 Since we found four blocks of motivations and three blocks of sources, there is enough evidence  
336 to conclude that preferential associations between specific motivations and specific seed  
337 sources exist. In particular, an association was found between seed sourcing through legacy and  
338 the motivations cited by men related to seed familiarity and knowledge, to crop attachment, and  
339 to other agronomic uses, and to motivations related to food processing cited by women (Block  
340 3). A broader range of seed sources was associated with other motivations, including legacy,  
341 but also market or interpersonal relationships and the motivations related to growth-cycle length  
342 that were frequently cited by both the men and the women, the motivations related to food uses  
343 and production quality cited by women, and other uses (e.g., fodder or building material  
344 production) cited by men (Block 1). There was also a range of less frequently cited motivations  
345 (Block 2).

346



348

349 *Figure 5: Network Sources-Motivations matrices on data aggregated for all the varieties of*  
 350 *the three species. A. (top): reordered table following the inferred blocks. B. (bottom): mean*  
 351 *number of interactions for each pair of blocks. For instance, on average, 20 women declared*  
 352 *having inherited seeds they use for food.*

353

354 The results of the LBM of the tripartite network variety X [motivations, seed sources] brought  
 355 a more detailed understanding of the observations described for the aggregated data (Figure 6).  
 356 They highlighted that the different varieties of pearl millet, groundnut, and cowpea were  
 357 sourced through different channels and associated with different motivations. The pearl millet  
 358 variety *Thioassane* was clearly distinguished from the rest of the varieties (Block 1), because it  
 359 was exclusively obtained by farmers through legacy, and it is the only variety men associated  
 360 with the motivations related to familiarity, attachment, food production, other agronomic  
 361 motivations (e.g. soil adaptation, low fertility requirement), climate adaptation, and production  
 362 (quantity and quality). This particular pattern for *Thioassane* variety probably explains the higher

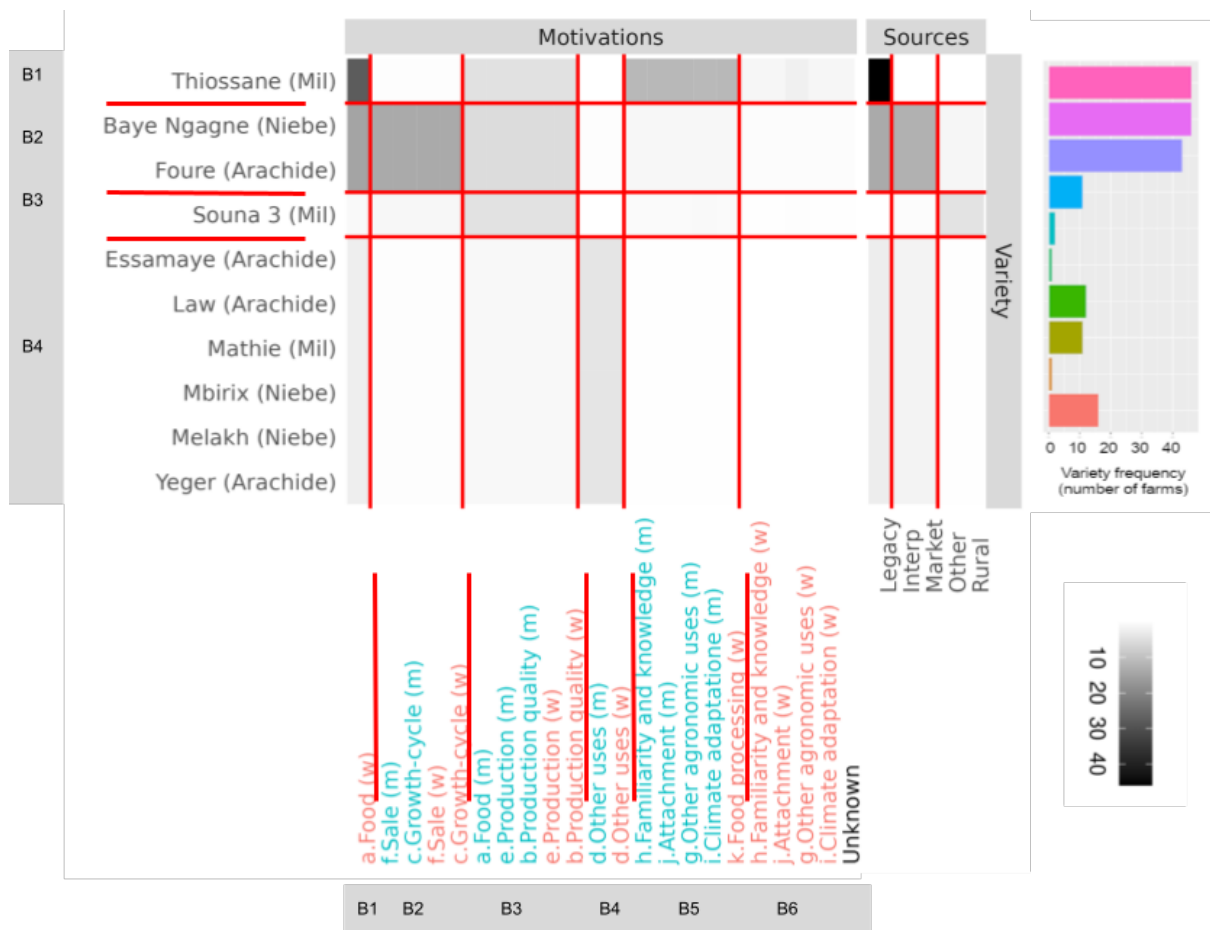
363 prevalence of seed sourcing through legacy observed for men in the general analysis on  
364 aggregated data presented above (Figure 5). Women associated *Thiossane* primarily with  
365 motivations related to food, and then to the quality of production and to food processing.  
366 *Thiossane* is a local traditional variety cultivated by all households for self-consumption as a  
367 staple food crop. It is mainly managed by men and transmitted from fathers to their sons (pers.  
368 obs.).

369  
370 One cowpea variety (*Baye Ngagne*) and one groundnut variety (*Foure*) presented similar  
371 profiles of motivations and seed sourcing (Block 2). They were obtained through different seed  
372 sources: legacy, interpersonal exchanges, or through the market. Both men and women  
373 dominantly associated them with motivations related to sale, to the growth-cycle length (early  
374 maturing), and to the quality of production (produced a lot of oil for *Foure* / produced big seeds  
375 for *Baye Ngagne*). Only women associated these varieties with food (good taste). *Foure* and  
376 *Baye Ngagne* were the most cultivated groundnut and cowpea varieties, respectively, used for  
377 both self-consumption (sauces preparation) and sale. *Foure* was distributed by the state in the  
378 1970's as a drought resistant variety, and the origin of *Baye Ngagne* is unclear (pers. obs.).

379  
380 Third, the pearl millet variety *Souna 3* was distinguished from the rest of the varieties (Block  
381 3), because it was the only one sourced from rural development organizations (associations) or  
382 other actors (official seed producers). Indeed, this variety was bred by the national research  
383 center and released at the end the 1970's. It is rarely cultivated, and was only present in one of  
384 the villages surveyed. It was only associated with motivations related to food and the quality of  
385 production (produces a large amount of flour) by both men and women.

386  
387 Last, all the other varieties, which were less frequently cultivated, were grouped in the last block  
388 (Block 4). It covers one pearl millet variety (*Mathie*), two cowpea varieties (*Mbirix* and *Melakh*)  
389 and three groundnut varieties (*Yeger*, *Law* and *Essamaye*). These varieties were also obtained  
390 through a range of seed sources (legacy, market, interpersonal), but were the only varieties  
391 associated with non-agronomic uses: primarily for the production of fodder and building  
392 material. Women also cited motivations related to food and to the quality of production of these  
393 varieties. They particularly valued the big size of *Yeger* seeds, the taste and the good flour  
394 production of *Mathie*, and the fact that *Mbirix* is late maturing, which allows them to get fresh  
395 seeds later, and also because it produces big seeds. *Mathie* is a local pearl millet variety that is

396 less cultivated nowadays because it has a long cycle and therefore less adapted to the shortened  
 397 rainy season, but the origin of *Mbirix* and *Yeger* is unclear (pers. obs.).  
 398



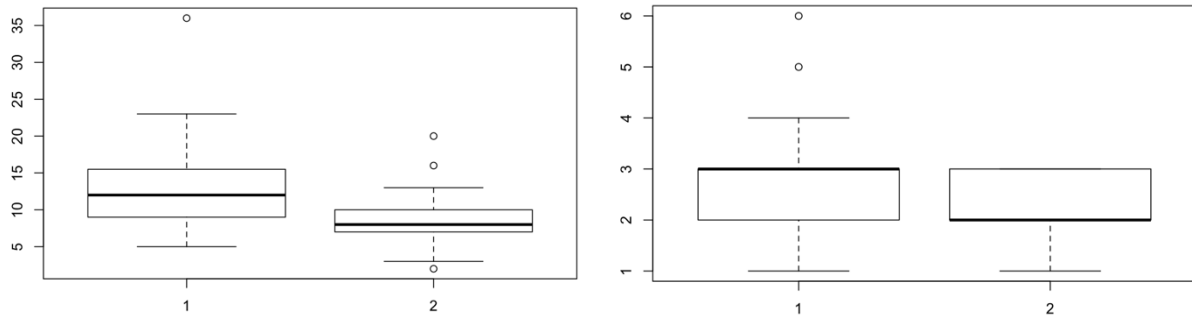
399  
 400 *Figure 6: Results of multi-stakeholder LBMs on the matrix « varieties X sources; motivations »*  
 401 *for the three species (right), and frequency of each variety in the village (left, number of*  
 402 *households cultivating each variety).*

403  
 404 **3.3. Identifying profiles of households depending on the combined seed sources and**  
 405 **motivations**

406  
 407 The analysis of the multipartite network of Households x [sources; motivations] with the three  
 408 target species taken separately indicated that the optimal number of blocks calculated through  
 409 the penalized likelihood criterion (ICL) was one or two (ICL of -1602 for one block versus -  
 410 1615 for two blocks). In order to highlight the different household strategy, we retained the  
 411 LBM results with two blocks of households (See figure in SI 3). The main difference between  
 412 the two blocks was that the first one groups together households that cited a broader range of  
 413 motivations for millet and groundnut, and to a lesser extent, a larger number of seed sources

414 than the second Block (Figure 7). This was probably related to the fact that the households in  
 415 Block 1 grew on average more varieties (4.8, sd=1.4) than in Block 2 (3.2, sd=0.9). No  
 416 particular differences in the socio-economic status of households belonging to each group were  
 417 detected.

418



419 *Figure 7. left: Mean number of motivations cited per household (Y axis) and its standard*  
 420 *deviation for each LBM block (Y axis). Right: Mean number of seed sources cited per*  
 421 *household (Y axis) and its standard deviation for each LBM block (X axis).*

422

#### 423 **4. Discussion**

424 Our joint analysis of the seed sources and motivations that Sereer farmers associated with  
 425 different crop varieties resulted in three main themes that will be elaborated in the following  
 426 discussion. First of all, this study emphasized that farmers combined a range of seed sourcing  
 427 channels, which in turn provided them with a range of NCPs that support their livelihoods and  
 428 well-being. Second, gender played an important role in shaping the number and type of seed  
 429 sources, as well as motivations for growing different varieties. Third, we discuss the  
 430 implications of the patterns of seed sources and motivations for vulnerability and resilience  
 431 within the farming systems. The Discussion is rounded out with a reflection on the limitations  
 432 of the study and future research directions.

433

#### 434 ***Farmers combine a range of seed sourcing channels to secure their access to NCPs necessary*** 435 ***for their livelihoods***

436 We found that Sereer farmers did not rely on a unique type of seed sourcing channel, but rather  
 437 mobilized a mix of different channels to meet a range of NCPs that are key for their livelihoods  
 438 and well-being. Farmers rarely obtained seeds through the official channels, and mainly relied  
 439 on legacy, exchange through peer-to-peer relationships, and on commercial relationships with

440 different types of seed sellers at local markets or shops. These results align with previous studies  
441 in Africa, showing that the so-called “formal” or official seed dissemination channels are rarely  
442 mobilized by farmers (McGuire and Sperling 2016). Reasons cited in the literature are mainly  
443 the high cost of buying certified seeds through the official channels, and that the benefit  
444 expected in terms of increased yield is frequently not attained by farmers due to sub-optimal  
445 growing conditions (e.g. limited access to fertilizer, water stress). Supply of seeds through  
446 formal channels can also be constrained by supplier interests and preferences. For example,  
447 suppliers tend to focus on just a few crops and varieties, they may sell at locations that are far  
448 away or not readily accessible, and they may price seeds too high for many smallholder farmers.  
449 Further, as in other smallholder agricultural systems (Almekinders and Louwaars 2002), we  
450 observed that varieties that would have been initially released by the official crop breeding  
451 system were frequently obtained by farmers through peer-to-peer seed circulation and through  
452 local markets, which is a common pattern for agricultural innovations (e.g. Röling, 2009;  
453 Teeken, et al. 2012). This was possible because the varieties released by the state crop breeding  
454 system were not hybrid ones. However, even if the official distribution channels represent a  
455 very small proportion of the seed sources documented in this study, their importance and  
456 contribution to the diversity of crops grown by farmers is potentially significant. Finally, the  
457 low prevalence of the State distribution channels in this study may not be representative of the  
458 situation in other places in Senegal (IPAR 2015), illustrating the importance of acknowledging  
459 the local context when considering smallholder systems.

460

461 The range of perceived NCPs provided by seed varieties obtained through this sourcing network  
462 is notable. While past research largely focused on utilitarian aspects, such as food and sale (e.g.,  
463 Greig 2009), this study highlighted the importance of cultural NCPs, as some crop varieties  
464 were pivotal to providing non-tangible benefits, such as cultural and place attachment. This is  
465 particularly important to recognize, as cultural NCPs are notoriously difficult to measure and  
466 value (e.g. Hirons, et al. 2016). Cultural values are often tied to specific environmental and  
467 social conditions, whereby farmers have adapted specific seed and crop varieties to reduce yield  
468 uncertainty. Over time, these varieties come to assume meaning beyond the materialistic  
469 benefits (food, profit etc.) (Rijal, 2010). Likely, a combination of these cultural values and other  
470 criteria (e.g. agronomic adaptation) served as the drivers of crop choice (Ficiciyan, et al. 2018;  
471 Velasquez-Mila, et al. 2011), making it difficult to delineate a single primary motivation for  
472 farmers’ decisions.

473

474 The complex and intertwined nature of the seed exchange system in this study is in line with  
475 previous observations concerning the high porosity between official seed dissemination  
476 channels and local networks (Almekinders and Louwaars, 2002). Our results provide evidence  
477 that counters the currently divided approaches to policy and development in the formal and  
478 informal seed systems (McGuire & Sperling, 2016; Hlatshwayo, et al. 2021). Rather, the results  
479 support proposals to consider the variety of seed sourcing channels as parts of a single  
480 integrated system, which should be treated as such for policy and investment decisions  
481 (Louwaars & de Boef, 2012).

482

### 483 *Gender discrepancies in source and motivations and differences between varieties*

484 This study also demonstrates how men and women diverge in terms of the relationships between  
485 seed sourcing, crop varieties, and the associated perceived benefits. These gender differences  
486 have implications both for acquiring new or improved crop varieties, and for the vulnerability  
487 and adaptive capacity of accessing desired NCPs.

488

489 First of all, this study showed that women relied on a more limited pool of sources for seeds  
490 than men. Men generally cited a wider range of seed sources than women for the three grain  
491 crop species. Interestingly, women mentioned the market and legacy as seed sources less  
492 frequently than men. Men cited rural organizations while women did not, suggesting that  
493 women have limited access to this source. Several processes may explain the gender differences  
494 observed in seed sources. First, men in the Sereer society are the ones in charge of pearl millet  
495 cultivation and seed management, and they traditionally get their seed through inheritance from  
496 their father, which probably explains the higher importance of this seed source for men as  
497 compared to women. Second, men dedicate more time than women to social interactions outside  
498 the household, while women have a considerably larger workload in the home. Men thus have  
499 more opportunities to connect to a larger range of seed providers than women. Men also possess  
500 more money than women, who mostly rely on their husbands for resources, which may explain  
501 the differential access to the market. As such, non-monetary seed sourcing channels such as  
502 peer-to-peer gifts or exchanges appear particularly pivotal for women to access seeds. Previous  
503 research in Africa supports these findings, showing how women rely mostly on their own seeds,  
504 personal connections, or local markets, rather than extension services, seed companies, or  
505 farmers groups (e.g., Marimo et al. 2021; McGuire & Sperling 2016). While social factors may  
506 influence where men and women source seeds, there is evidence from other studies that policies

507 and programs that empower women or put them in decision-making positions can encourage  
508 more agrobiodiversity (e.g. Assefa, et al. 2022; Valencia, et al. 2021).

509  
510 Men and women also perceived different NCPs in relation to the crop varieties. For instance,  
511 the millet landrace *Thiossane* was associated primarily with food uses by women, and with  
512 motivations related to familiarity and attachment or agronomic uses by men. Indeed, *Thiossane*  
513 is a men's crop in the Sereer society, transmitted from a father to his sons, creating a strong  
514 cultural attachment to the crop not seen among the women. Conversely, women are in charge  
515 of food preparation, which explains the importance they place on these motivations, which were  
516 also observed for the other crop species. This corroborates other studies that have found  
517 gendered rationale for crop choice, although these motivations vary by cultural and  
518 geographical context (Nordhagen, et al. 2021; Sari, et al. 2020; Oakley & Momsen, 2004). For  
519 instance, one study in Southeast Sulawesi found that men selected timber and fruit trees for  
520 shade based on economic benefits, while women cited production for household needs (Sari, et  
521 al. 2020). Conversely, in Papua New Guinea, women tended to be more motivated by marketing  
522 potential, and men by tradition and status (Nordhagen, et al. 2021). That said, the literature  
523 connecting gender and NCPs (here, the ecosystem services term is used) in general is very  
524 limited (Yang, et al. 2018).

525  
526 Perceived NCP varied by variety for the different species. For millet, the motivations cited for  
527 the three varieties cultivated locally differed considerably: *Thiossane* landrace was associated  
528 to immaterial NCP, particularly attachment, while *Souna 3* variety was exclusively associated  
529 to production quality and quantity, and *Mathie* landrace was mainly associated to other uses,  
530 such as fodder and building material production. Similar patterns were observed for cowpea  
531 and groundnut, with *Baye Ngagne* and *Foure* varieties dominantly associated with motivations  
532 related to their growth cycle and to their marketability, respectively, and *Mbirix* and *Yeger* more  
533 frequently motivated by other uses (mainly fodder production).

### 534 535 ***Implications for the resilience of agricultural systems***

536 Our results showed that different seed channels are complementary from farmers' perspectives,  
537 as they allow them to access different crop varieties that provide different NCPs. For instance,  
538 legacy allows farmers to obtain seeds from local traditional *Thiossane* millet landrace  
539 associated with tradition, heritage, and identity (in addition to agronomic and use benefits),  
540 while commercial channels provide them with the *Foure* groundnut variety related to



541 marketability and agronomic properties/adaptation (material and regulating NCP). We also  
542 observe redundancy as farmers mobilized different seed sources to get varieties associated with  
543 key NCPs for their livelihoods. For instance, cowpea variety *Baye ngagne*, which was pivotal  
544 for both women's income and food provision, was obtained through a range of seed sources.  
545 This redundancy can improve the resilience of seed provisioning, providing alternatives when  
546 seeds are no longer available from one source (Matsuhita, et al. 2016; Massawe, et al. 2016).  
547 Diversifying seed sources as a possible strategy to mitigate perturbations appears to be a  
548 practice shared by most households in this study, who demonstrated very similar seed sourcing  
549 practices and cited similar motivations.

550

551 The relationships between seed sourcing practices and NCPs based on the gender of Sereer  
552 farmers also highlights areas of potential resilience and vulnerability to shocks in this  
553 agricultural system. A study in Bangladesh similarly suggested that gendered choices of  
554 crops/agrobiodiversity may ultimately impact on the capacity to adapt to stressors like climate  
555 change (Bhattari, et al. 2015). Women in this study perceived multiple NCPs for each crop  
556 species; however, crop species were acquired from a limited number of sources. Men, on the  
557 other hand, had redundancy in the mapping of NCPs to a variety of sources, even within some  
558 crop species. This duplication of NCPs among crops and sources may indicate the ability to fall  
559 back on or exchange crops/seed sources based on the conditions. Consequently, the limited  
560 number of sources for seeds potentially makes Sereer women vulnerable to the loss of some  
561 NCPs under shocks.

562

563 To the best of our knowledge, the gender differences between the combination of crops, seed  
564 sourcing practices and NCPs have never been highlighted in the literature. Gender is known to  
565 be a key factor to consider in policies for rural development, given the well documented  
566 differences in risks, vulnerabilities, and barriers between men and women (Denton, 2002;  
567 Huyer, 2016; Jost, et al. 2016). Therefore, understanding these differences can guide initiatives  
568 and rural development policies aimed at supporting and securing farmers' access to seeds.

569

### 570 ***Limitations and future research directions***

571 The examination of seed sources, crop choice, and associated NCPs is still an active field of  
572 research. As such, there are several areas to take this work further, and limitations in the current  
573 study. For one, while seeds may originate from a variety of sources and due to a suite of  
574 motivations, how those differ between households appeared to be fairly limited in this study.

575 The main difference between households was for the number of motivations, and to a lesser  
576 extent the number of seed sources, that were reported for the three species at the household  
577 level. Future investigations would be required to understand the factors explaining the inter-  
578 household differences in the number of motivations and seed sources cited. It is also worth  
579 noting that we limited our analysis to what was elicited by farmers, and so in some cases  
580 motivations for both the variety and for the source may be highly intermingled and thus difficult  
581 to tease apart.

582

583 One limitation of our work is that we only documented the final seed sourcing events for each  
584 variety cultivated by farmers, while monitoring over several years would allow us to develop a  
585 better understanding of seed flows in smallholder farming communities. Documenting only the  
586 last source of seeds limits our capacity to discuss implications for farm resilience over time and  
587 to future shocks. Our study could be taken further using panel data to monitor seed sourcing  
588 networks and NCP provision over time, which would help elucidate which properties of  
589 farmers' seed sourcing networks are key for maintaining the different NCPs in the face of  
590 shocks to the agricultural system.

591

592 Finally, several studies have highlighted the importance of the local farmer seed exchange  
593 networks for maintaining food sovereignty and security, hedging against crop failure,  
594 strengthening social cohesion of families and communities, and maintaining agrobiodiversity  
595 (Niekerk & Wynberg, 2017, Khadka, et al. 2018). Both food sovereignty, including the control  
596 over seed stocks (e.g. Bezner Kerr, 2013; Helicke, 2015), and food security can be objectives  
597 stemming from seed sourcing networks; however, these areas of scholarship often diverge.  
598 Exploring the role of seed networks in achieving these related, but often siloed, ultimate  
599 objectives was outside the scope of this study, yet would be a compelling area for additional  
600 research.

601

## 602 **5. Conclusion**

603 This study illustrates how representing the interactions between crop varieties (biological  
604 entities), seed sources (social entities), and NCPs in the form of SEN networks opens new ways  
605 for analyzing such complex systems of interactions. Analyzing these relationships brings  
606 insights on the resilience of farmers by identifying how vulnerable is the provision of the  
607 different NCPs to the disruption of particular seed sources. Our results showed that the  
608 maintenance of a range of NCPs, which are instrumental for households' resilience, relies not

609 exclusively on interpersonal seed exchanges or official seed diffusion channels, but on a  
610 diversity of seed sources that allow farmers to get a range of crops, and which are  
611 complementary. Our study therefore indicates that the development initiatives aimed at  
612 centralizing and structuring seed diffusion don't match with smallholder needs and may  
613 compromise their resilience. Instead, the coexistence of different types of seed sources and their  
614 intertwining should be further supported by development policies to enhance smallholder  
615 resilience to global changes.

616

### 617 **Acknowledgements**

618 We gratefully acknowledge the farmers and local authorities in the study area for the time they  
619 dedicated to our survey, as well as Robert Diatte for helping with surveys, translation, and  
620 guiding us during fieldwork. We benefited from the support of the Niakhar Health and  
621 Demographic Surveillance System for conducting this study. This project was supported by  
622 Agropolis Fondation under the reference 1603-002 through the “Investissements d’avenir”  
623 program (Labex Agro:ANR-10-LABX-0001-01). We thank the researchers from the GDR  
624 ReSoDiv (funded by the CNRS) for rich discussions that significantly contributed to this paper.  
625 We acknowledge funding from the National Socio-Environmental Synthesis Center (SESYNC)  
626 for a workshop that developed this research, under funding received from the National Science  
627 Foundation (NSF) DBI-1639145. We thank other participants of the workshop, and particularly  
628 Jesse Sayles, Jaime Ashander and Kailin Kroetz for fruitful exchanges. We thank M. Dieye for  
629 producing the map of the study site.

630

### 631 **References**

- 632 Almekinders, C.J., and Louwaars, N.P. (2002). The importance of the farmers' seed  
633 systems in a functional national seed sector. *Journal of New Seeds* 4, 15–33.
- 634 Altieri, M.A., and Nicholls, C.I. (2017). The adaptation and mitigation potential of  
635 traditional agriculture in a changing climate. *Climate Change* 140, 33–45.
- 636 Assefa, W., Kewessa, G., and Datiko, D. (2022). Agrobiodiversity and gender: the role  
637 of women in farm diversification among smallholder farmers in Sinana district,  
638 Southeastern Ethiopia. *Biodiversity and Conservation* 1–20.
- 639 Bar-Hen, A., Barbillon, P., and Donnet, S. (2020) Block models for generalized  
640 multipartite networks: Applications in ecology and ethnobiology. *Statistical Modelling*.
- 641 Benoit-Cattin, M., and Faye, J. (1982). *L'exploitation agricole familiale en Afrique*  
642 *soudano-sahélienne* (PUF).

643 Berg, T. (2009). Landraces and folk varieties: a conceptual reappraisal of terminology.  
644 *Euphytica* 166: 423-30.

645 Bezner Kerr, R. (2013). Seed struggles and food sovereignty in northern Malawi.  
646 *Journal of Peasant Studies*, 40(5), 867-897.

647 Bhattarai, B., Beilin, R., and Ford, R. (2015). Gender, agrobiodiversity, and climate  
648 change: A study of adaptation practices in the Nepal Himalayas. *World Development*  
649 70, 122–132.

650 Bodin, Ö., Alexander, S.M., Baggio, J., Barnes, M.L., Berardo, R., Cumming, G.S.,  
651 Dee, L.E., Fischer, A.P., Fischer, M., and Garcia, M.M. (2019). Improving network  
652 approaches to the study of complex social–ecological interdependencies. *Nature*  
653 *Sustainability* 2, 551–559.

654 Cabell, J.F., and Oelofse, M. (2012). An indicator framework for assessing  
655 agroecosystem resilience. *Ecology and Society* 17.

656 Calvet-Mir, L., Calvet-Mir, M., Molina, J. L., and Reyes-García, V. (2012). Seed  
657 exchange as an agrobiodiversity conservation mechanism. A case study in Vall Fosca,  
658 Catalan Pyrenees, Iberian Peninsula. *Ecology and Society*, 17(1).

659 Carrington, P. J., Scott, J., & Wasserman, S. (Eds.). (2005). *Models and methods in*  
660 *social network analysis* (Vol. 28). Cambridge university press.

661 Chiquet, J., Donnet, S., and Barbillon, P. (2021). sbm: Stochastic Blockmodels  
662 [Online]. Available: <https://cran.r-project.org/package=sbm>.

663 Cobelli, O., Faye, N.F., Beaurepaire, S., Raimond, C., Labeyrie, V. (In Press). Modes  
664 de gestion de la diversité cultivée par les paysans dans le bassin arachidier au  
665 Sénégal : la coexistence comme nouvelle normalité ? *Droits et Cultures*

666 Croft, M.M., Marshall, M.I., Odendo, M., Ndinya, C., Ondego, N.N., Obura, P., and  
667 Hallett, S.G. (2018). Formal and informal seed systems in Kenya: Supporting  
668 indigenous vegetable seed quality. *The Journal of Development Studies* 54, 758–775.

669 Dee, L.E., Thompson, R., Massol, F., Guerrero, A., and Bohan, D.A. (2017). Do  
670 Social–Ecological Syndromes Predict Outcomes for Ecosystem Services?—a Reply to  
671 Bodin et al. *Trends in Ecology & Evolution*.

672 Delaquis, E., Andersen, K., Minato, N., Le Cu, T.T., Karssenberg, M.E., Sok, S.,  
673 Wyckhuys, K.A., Newby, J.C., Burra, D.D., and Srean, P. (2018). Raising the stakes:  
674 cassava seed networks at multiple scales in Cambodia and Vietnam. *Frontiers in*  
675 *Sustainable Food Systems* 2: 73. Doi: 10.3389/Fsufs.

676 Delaunay, V., Douillot, L., Diallo, A., Dione, D., Trape, J.-F., Medianikov, O., Raoult,  
677 D., and Sokhna, C. (2013). Profile: the Niakhar health and demographic surveillance  
678 system. *International Journal of Epidemiology* 42, 1002–1011.

679 Demongeot, M., Chaplin-Krammer, B., and Pascual, U. (2022). IPBES VA Chapter 4  
680 - Literature review on values articulated in agrobiodiversity management (Version  
681 02). Zenodo. <https://doi.org/10.5281/zenodo.6502719>

682 Denton, F. (2002). Climate change vulnerability, impacts, and adaptation: Why does  
683 gender matter? *Gender & Development* 10, 10–20.

684 Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., Hill,  
685 R., Chan, K.M., Baste, I.A., and Brauman, K.A. (2018). Assessing nature’s  
686 contributions to people. *Science* 359, 270–272.

687 Felipe-Lucia, M.R., Guerrero, A.M., Alexander, S.M., Ashander, J., Baggio, J.A.,  
688 Barnes, M.L., Bodin, Ö., Bonn, A., Fortin, M.-J., and Friedman, R.S. (2022).  
689 Conceptualizing ecosystem services using social–ecological networks. *Trends in*  
690 *Ecology & Evolution*, 37 (3), 211-222.

691 Ficiciyan, A., Loos, J., Sievers-Glotzbach, S., & Tschardtke, T. (2018). More than  
692 yield: Ecosystem services of traditional versus modern crop varieties revisited.  
693 *Sustainability*, 10(8), 2834.

694 Guigou, B. (1992). *Les changements du système familial et matrimonial: Les Sérères*  
695 *du Sine (Sénégal)*. Paris, EHESS.

696 Greig, L. (2009). An analysis of the key factors influencing farmer’s choice of crop,  
697 Kibamba Ward, Tanzania. *Journal of Agricultural Economics*, 60(3), 699-715.

698 Helicke, N. A. (2015). Seed exchange networks and food system resilience in the  
699 United States. *Journal of Environmental Studies and Sciences*, 5, 636-649.

700 Hiron, M., Comberti, C., and Dunford, R. (2016). Valuing cultural ecosystem  
701 services. *Annual Review of Environment and Resources* 41, 545–574.

702 Hlatshwayo, S.I., Modi, A.T., Hlahla, S., Ngidi, M., and Mabhaudhi, T. (2021).  
703 Usefulness of seed systems for reviving smallholder agriculture: A South African  
704 perspective. *African Journal of Food, Agriculture, Nutrition and Development* 21,  
705 17581–17603.

706 Huyer, S. (2016). *Closing the gender gap in agriculture* (SAGE Publications Sage  
707 India: New Delhi, India).

708 IPAR, Initiative Prospective Agricole Rurale. (2015). *Subventions des intrants*  
709 *agricoles au Sénégal : Controverses et Réalités. Rapport annuel sur l’état de l’agriculture*

710 et du monde rural au Sénégal.

711 Jackson, L., van Noordwijk, M., Bengtsson, J., Foster, W., Lipper, L., Pulleman, M.,  
712 Said, M., Snaddon, J., and Vodouhe, R. (2010). Biodiversity and agricultural sustainability:  
713 from assessment to adaptive management. *Current Opinion on Environmental Sustainability* 2,  
714 80–87.

715 Jost, C., Kyazze, F., Naab, J., Neelormi, S., Kinyangi, J., Zougmore, R., Aggarwal, P.,  
716 Bhatta, G., Chaudhury, M., and Tapio-Bistrom, M.-L. (2016). Understanding gender  
717 dimensions of agriculture and climate change in smallholder farming communities.  
718 *Climate and Development* 8, 133–144.

719 Khadka, K., Gartaula, H., Shrestha, A., Upadhyay, D., Chaudhary, P., Patel, K., &  
720 Devkota, R. (2018). Farmers' seed networks and agrobiodiversity conservation for  
721 sustainable food security: a case from the mid-hills of Nepal. *International Journal on*  
722 *Biodiversity Watch*, 4, 109-133

723 Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L.,  
724 Jarvis, A., Rieseberg, L.H., and Struik, P.C. (2014). Increasing homogeneity in global  
725 food supplies and the implications for food security. *Proceedings of the National*  
726 *Academy of Sciences*, 111, 4001–4006.

727 Kilwinger, F. B., Marimo, P., Rietveld, A. M., Almekinders, C. J., & van Dam, Y. K.  
728 (2020). Not only the seed matters: Farmers' perceptions of sources for banana planting  
729 materials in Uganda. *Outlook on Agriculture*, 49(2), 119-132.

730 Kremen, C., and Merenlender, A.M. (2018). Landscapes that work for biodiversity  
731 and people. *Science*, 362, eaau6020.

732 Labeyrie, V., Deu, M., Barnaud, A., Calatayud, C., Buiron, M., Wambugu, P., Manel,  
733 S., Glaszmann, J.-C., and Leclerc, C. (2014). Influence of ethnolinguistic diversity on  
734 the sorghum genetic patterns in subsistence farming systems in Eastern Kenya. *PloS*  
735 *One*, 9, e92178.

736 Louwaars, N.P., and De Boef, W.S. (2012). Integrated seed sector development in  
737 Africa: a conceptual framework for creating coherence between practices, programs,  
738 and policies. *Journal of Crop Improvement*, 26, 39–59.

739 Louwaars, N.P., and Manicad G. (2022). Seed Systems Resilience—An Overview.  
740 *Seeds*, 1 (4): 340-56.

741 Marimo, P., Otieno, G., Njuguna-Mungai, E., Vernoooy, R., Halewood, M., Fadda, C.,  
742 Mulumba, J.W., Nyamongo, D.O., and Mollel, M. (2021). The Role of Gender and

743 Institutional Dynamics in Adapting Seed Systems to Climate Change: Case Studies  
744 from Kenya, Tanzania and Uganda. *Agriculture*, 11, 840.

745 Martin, A.R., Cadotte, M.W., Isaac, M.E., Milla, R., Vile, D., and Violle, C. (2019).  
746 Regional and global shifts in crop diversity through the Anthropocene. *PloS One*, 14.  
747 Massawe, F., Mayes, S., & Cheng, A. (2016). Crop diversity: an unexploited treasure  
748 trove for food security. *Trends in plant science*, 21(5), 365-368.

749 Matsushita, K., Yamane, F., & Asano, K. (2016). Linkage between crop diversity and  
750 agro-ecosystem resilience: Nonmonotonic agricultural response under alternate  
751 regimes. *Ecological Economics*, 126, 23-31.

752 McGuire, S., and Sperling, L. (2013). Making seed systems more resilient to stress.  
753 *Global Environmental Change*, 23, 644–653.

754 McGuire, S., and Sperling, L. (2016). Seed systems smallholder farmers use. *Food*  
755 *Security*, 8, 179–195.

756 Morton, J.F. (2007). The impact of climate change on smallholder and subsistence  
757 agriculture. *Proceedings of the National Academy of Sciences*, 104, 19680–19685.

758 van Niekerk, J., and Wynberg, R. (2017). Traditional seed and exchange systems  
759 cement social relations and provide a safety net: A case study from KwaZulu-Natal,  
760 South Africa. *Agroecology and Sustainable Food Systems*, 41, 1099–1123.

761 Nordhagen, S., Pascual, U., and Drucker, A.G. (2021). Gendered differences in crop  
762 diversity choices: A case study from Papua New Guinea. *World Development*, 137,  
763 105134.

764 Oakley, E., and Momsen, J. H. (2005). Gender and agrobiodiversity: a case study from  
765 Bangladesh. *Geographical Journal*, 171(3), 195-208.

766 Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., Watson R.T,  
767 Başak Dessane E., Islar, M., et Kelemen, E. (2017). Valuing nature’s contributions to  
768 people: the IPBES approach. *Current Opinion in Environmental Sustainability*, 26:  
769 7-16.

770 Renard, D., and Tilman D. (2021). Cultivate biodiversity to harvest food security and  
771 sustainability. *Current Biology*, 31 (19): R1154-58.

772 Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., and Chookolingo, B. (2018).  
773 How much of the world’s food do smallholders produce? *Global Food Security*, 17,  
774 64–72.

775 Rijal, D. K. (2010). Role of food tradition in conserving crop landraces on-farm.  
776 *Journal of Agriculture and Environment*, 11, 107-119.

777 Röling, N. (2009). Pathways for impact: scientists' different perspectives on  
778 agricultural innovation. *International journal of agricultural sustainability*, 7(2): 83-94.

779 Sari, R. R., Saputra, D. D., Hairiah, K., Rozendaal, D., Roshetko, J. M., and Van  
780 Noordwijk, M. (2020). Gendered species preferences link tree diversity and carbon  
781 stocks in cacao agroforest in Southeast Sulawesi, Indonesia. *Land*, 9(4), 108.

782 Sayles, J. S., Garcia, M. M., Hamilton, M., Alexander, S. M., Baggio, J. A., Fischer,  
783 A. P., Ingold, K., Meredith, G.R and Pittman, J. (2019). Social-ecological network  
784 analysis for sustainability sciences: a systematic review and innovative research  
785 agenda for the future. *Environmental Research Letters*, 14(9), 093003.

786 Schipanski, M. E., MacDonald, G. K., Rosenzweig, S., Chappell, M. J., Bennett, E.  
787 M., Kerr, R. B., Bennett E.M., Bezner Kerr, R., Blesh, J., Crews, T., Drinkwater, L.,  
788 Lundgren J.G., and Schnarr, C. (2016). Realizing resilient food systems. *BioScience*,  
789 66(7), 600-610.

790 Steenkamp, J. B., and Van Trijp, H. (1997). Attribute elicitation in marketing  
791 research: A comparison of three procedures. *Marketing Letters*, 8(2), 153-165.

792 Sultan, B., Dardel, C., Guichard, F., Kergoat, L., Lebel, T., Peugeot, C., Weigel, J-Y.,  
793 and Sinaba, F. (2015). Semi-arid zones: the Sahel is sensitive to variations in rainfall.

794 Tadesse, Y., Almekinders, C.J., Schulte, R.P., and Struik, P.C. (2017). Tracing the  
795 seed: seed diffusion of improved potato varieties through farmers' networks in  
796 chench, ethiopia. *Experimental Agriculture*, 53, 481–496.

797 Teeken, B., Nuijten, E., Temudo, M. P., Okry, F., Mokuwa, A., Struik, P. C., and  
798 Richards, P. (2012). Maintaining or abandoning African rice: lessons for  
799 understanding processes of seed innovation. *Human ecology*, 40(6), 879-892.

800 Urrea-Hernandez, C., Almekinders, C. J. M., and Van Dam, Y. K. (2016).  
801 Understanding perceptions of potato seed quality among small-scale farmers in  
802 Peruvian highlands. *NJAS-Wageningen Journal of Life Sciences*, 76, 21-28.

803 Valencia, V., Wittman, H., Jones, A. D., and Blesh, J. (2021). Public Policies for  
804 Agricultural Diversification: Implications for Gender Equity. *Frontiers in Sustainable*  
805 *Food Systems*, 5: 718449. doi: 10.3389/fsufs.

806 Velásquez-Milla, D., Casas, A., Torres-Guevara, J., and Cruz-Soriano, A. (2011).  
807 Ecological and socio-cultural factors influencing in situ conservation of crop diversity  
808 by traditional Andean households in Peru. *Journal of Ethnobiology and*  
809 *Ethnomedicine*, 7(1), 1-20.



810 Yang, Y. E., Passarelli, S., Lovell, R. J., and Ringler, C. (2018). Gendered  
811 perspectives of ecosystem services: A systematic review. *Ecosystem Services*, *31*, 58-  
812 67.  
813