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

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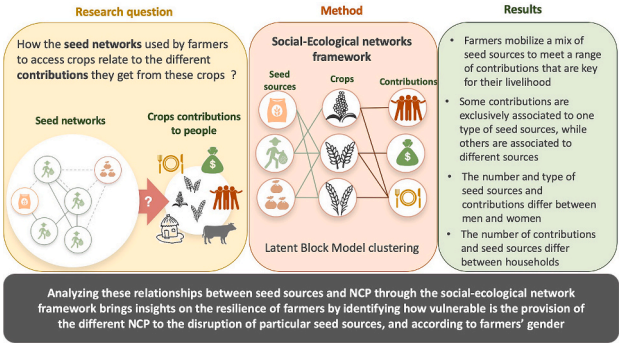
HIGHLIGHTS

- Farmers mobilize a mix of seed sources for key livelihood and cultural benefits including food production and attachment.
- Some contributions are exclusively associated with one seed source type, e.g. attachment relates only to legacy.
- Women relied on a more limited pool of sources for seeds than men, and mentioned the market and legacy less frequently.
- Two groups of households were identified based on differences in contributions and the number of seed sources mentioned.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: 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 farmers accessing 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 that affect these distribution channels.

OBJECTIVE: 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.

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METHODS: Field surveys were conducted with 85 farmers, half men and half women, 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.
RESULTS AND CONCLUSIONS: We found that some crops contributions were related to different seed sources, for instance crops associated to food provision were sourced through markets, peers, and legacy, while other contributions were related to one seed source type, for instance crops associated to attachment were sourced exclusively through legacy. Women relied on a more limited pool of seed sources than men, and they preferentially source seeds from peers. Last, two groups of households were differentiated based on the number of crops contributions and of seed sources they mentioned.
SIGNIFICANCE: Our study brings insights on how the observed social-ecological network patterns affect the access of men and women farmers to NCPs, and the consequences for the maintenance of NCP provision in the face of perturbations. It contributes to unraveling the processes involved in the resilience of small farms that rely on crop diversity for their livelihoods.

1. Introduction

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

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

Crop diversity is clearly linked to the ability of smallholder farmers to access a range of different seed varieties. Smallholder farmers access seeds for different crops through numerous channels (McGuire and Sperling, 2016). Although smallholder farmers often rely on barter or exchange with peers or monetized transactions at local markets and shops to get seeds, they tend to mobilize a wide range of other seed sources such as NGOs, private seed companies, and government programs (Almekinders and Louwaars, 2002). A number of studies have examined seed circulation networks in smallholder communities in various contexts, and this literature shows that modalities of seed sourcing can vary substantially across sites (e.g. Delaquis et al., 2018; Tadesse et al., 2017), even within the same country (Cobelli et al., 2023). Recent studies indicate that farmers' seed sourcing practices are related to the delivery of a range of NCPs (Urrea-Hernandez et al., 2016; Kilwinger et al., 2020); however, quantitative studies on this topic are lacking despite the importance of this relationship for household resilience.

Seed distribution and exchange channels influence the types of crops that farmers access (Louwaars and Manicad, 2022), therefore impacting the types of NCPs farmers receive. Studies in parts of Africa have highlighted how local seed networks and national seed distribution channels allow farmers to access a variety of types of crops with different functions (McGuire and Sperling, 2013, 2016). For instance, some crop species and landraces—local crop varieties that have been reproduced over several generations by farmers in a given location—can be accessed by farmers only through local networks, because they are not distributed through official channels. This has been observed for indigenous vegetables that have important nutritional properties and are adapted to local conditions (Croft et al., 2018), and for cereal landraces culturally valued locally (Labeyrie et al., 2014). On the other hand, the seed dissemination channels of private seed companies or state extension services allow farmers to access varieties resulting from targeted breeding efforts, with productivity advantages such as a short growth cycle duration or a high yield in favorable growing conditions. Despite the importance of combining official seed distribution channels with farmers' seed networks to enhance the resilience of small farms (McGuire and Sperling, 2013, 2016), relatively little is known about how seed sourcing practices relate to the NCPs that farmers obtain from crops.

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

Here we mobilize these recent developments in SEN research to conceptualize and examine how farmers access different NCPs through the seed sourcing channels of various crop varieties, through a case study in Sahelian Senegal. Via interviews and surveys, we first identified the main seed sources for farmers in the area (e.g. inherited seeds, acquired via peers, local markets, etc.), and then we assessed the main motivations for growing the different chosen seed varieties. These motivations were used as proxies for NCPs and categorized as regulating,

material, or non-material benefits according to the NCP framework (Pascual et al., 2017; Díaz et al., 2018). Then, we tested if particular seed sources were associated with particular motivations and if differences existed between men and women, and between households. Considering the strength of networks in capturing the interrelations and interdependencies between variables of interest, employing a SEN framing supports this study's aim to analyze the relationships between seed sources, seed varieties, and NCPs. In addition, the statistical analysis tools developed for network analysis allow dealing with the non-independence of observations, which is not possible with classical statistical methods. In the next sections, we detail the methods to collect and analyze the network data, and then report on the results. Finally, we discuss how the observed SEN patterns affect the access of men and women farmers to crop diversity, and consider the associated consequences for the maintenance of NCP provisioning in the face of shocks to the agricultural system for both gender groups.

2. Methods

2.1. Study site

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

The Sereer farmers, who make up nearly 97% of the inhabitants living in this area, are agro-pastoralists (Delaunay et al., 2013). They grow both cereals, mainly pearl millet (*Pennisetum glaucum*), and legumes, mainly cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogeae*), for self-consumption, animal feed, and for local sale. These crops are grown either in association or in rotation on sandy soils in agroforestry systems with *Faidherbia* trees. Plots are usually delineated with roselle (*Hibiscus sabdariffa*) hedgerows, the flowers of which are sold by women at local markets. Fallow is rare, as land is fully occupied in the area due to rapid population growth and urbanisation since the end of the twentieth century. A few vegetables are also grown near the house for preparing sauces, such as okra (*Abelmoschus esculentus*) and *cucurbitaceae*. A range of commercial farming activities, such as watermelon cultivation or cattle raising for meat, are developing in the area. Farmers in surveyed villages have limited access to chemical inputs, and they only rely on animal-driven tools for plowing, sowing, and harvesting. Irrigation is also not possible in the area due to groundwater salinity. A recent study details the patterns of crop diversity and its management practices in the two studied villages (Cobelli et al., 2023), indicating that farmers grow an average of 6 species, and between 1 and 2 varieties for each of the three species targeted in this study. Seed lots from different origins can be sown for a given variety within a household (i.e. multiple seed sources).

Households are organized into concessions, which group together

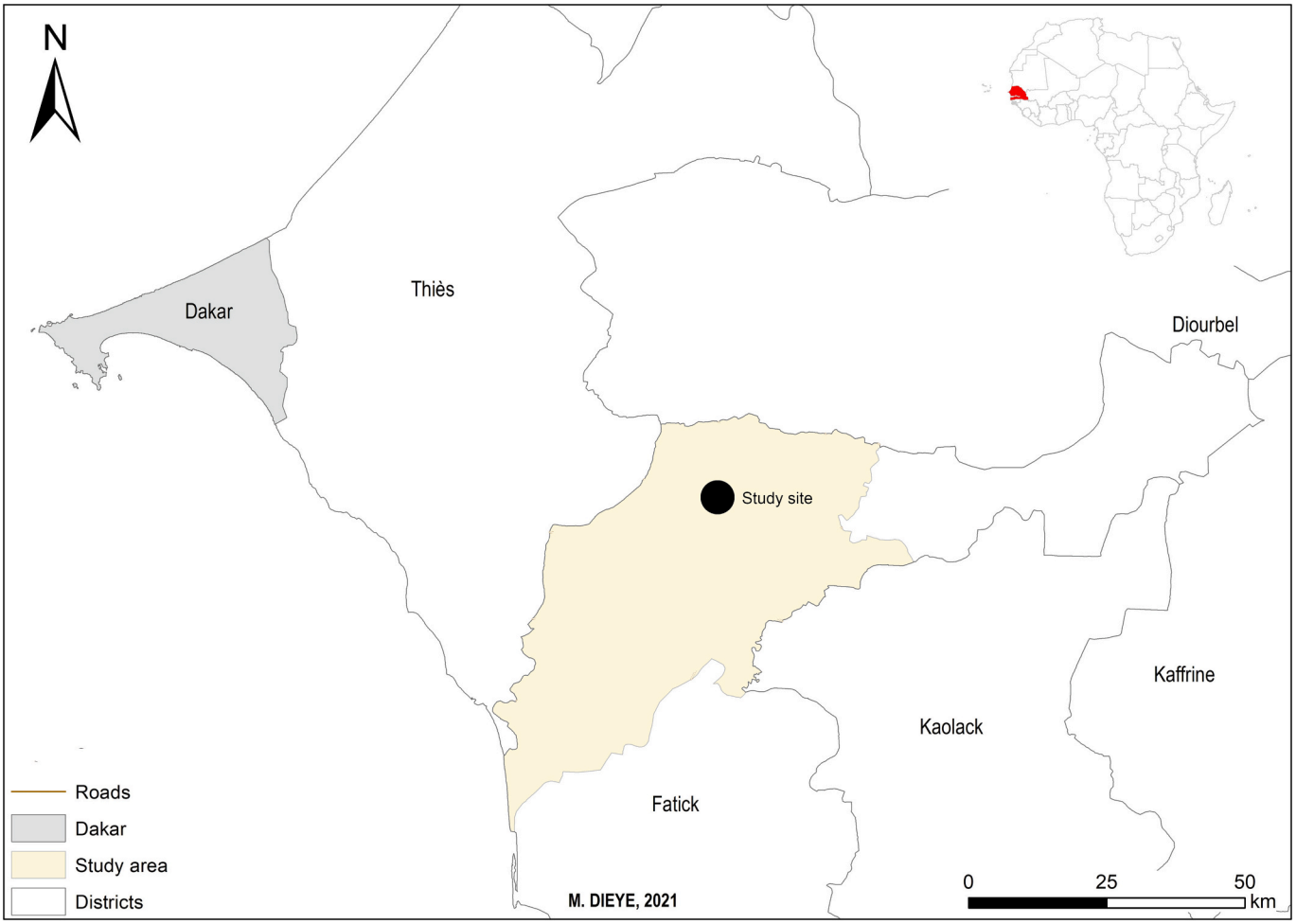

Fig. 1. Study site location.

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

2.2. Ethics approval

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

2.3. Data collection

Surveys were conducted between March and June 2018 in the two selected villages. The first part of the study aimed to obtain general information about the agrarian context of each village through semi-structured interviews with each village leader. We also carried out a census of households in each village in consultation with the village leader, and established a typology of households according to their economic status based on key descriptors (total area cultivated, farm equipment, availability of labor, working animals). This typology led to the construction of three classes (rich, middle-income, poor). We selected a stratified random sample of three low income households, four middle-income, and three rich households. We then employed snowball sampling and conducted surveys with all the households cited as seed providers by the heads of these 10 households. Snowball sampling is appropriate given the cultural context, where personal introductions and referrals are key in order to elicit responses. Further, albeit non-random, snowball sampling is often the method of choice when eliciting social network data (Carrington et al., 2005), which was the initial purpose of the project in which this study takes place.

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

The survey included four sections that applied to both male and female household heads on each farm. The first part of the survey aimed at collecting socio-economic and demographic information concerning the household and both household heads. The second part of the survey was an inventory of crop species and varieties of millet, groundnut, and cowpea cultivated on the farm in 2017. We selected these three crop species, because they are the main staple crops grown in the area and have different functions for households. The inventory of crop varieties was based on the names cited by the respondents, which reflect how farmers manage their genetic resources (Berg, 2009). Collective discussions at each site helped to identify possible synonyms (same biological object associated with different names) and to homogenize the names of varieties. This inventory therefore does not reflect the varietal diversity characterized by genetic markers, but rather that identified and named by farmers. The third part of the survey aimed at documenting seed sources mobilized by farmers, asking where farmers obtained the seeds of each variety of the three selected species cultivated in 2017 during their last and most recent seed sourcing event outside of the farm (i.e. external sourcing that could have occurred prior to 2017). A seed sourcing event is the instance of the seed of one variety sourced by a farm and coming from another source. Self-sourcing events were excluded, as we were interested only in external sourcing. This allowed us to document the origin of the current seed lots cultivated on the farms, prior to any further on-farm reproduction, if relevant. The last seed sourcing event was chosen, because previous studies have linked the overall level of crop diversity on-farm to the diversity of the last seed sourcing events (e.g. Calvet-Mir et al., 2012). The modes of seed supply were grouped into 5 main categories (Table 1.a).

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

2.4. Data analysis

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

The three objectives and associated socio-ecological networks are:

(i) ***Objective 1: understanding relationships between sources and motivations***. First, we aimed to identify the most frequently cited seed sources and motivations, and whether there were particular associations between the motivations and the seed sources, when considering all the varieties together for all the three species. Conducting an analysis for the three main crop species cultivated by farmers makes sense, because farmers manage them together due to their complementary and sometimes redundant functions in the farming system. We analyzed the “sources x motivations” weighted bipartite network (network 1) where

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

a. Seed Sources	Details	Type of seed
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. Nature Contributions to People (NCP)	Motivations	Examples
Regulation NCP		
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
Material NCP		
2. Production	2.1. Crop variety that provides a good quantity of production, all the year long	High yield crop with multiple harvest opportunities
	2.2. Crop variety that is suitable for processed products, and with good quality	Good for flour/oil production, big seeds / pods
3. Food preparation and consumption	3.1. Crop variety that provides tasty and nutritious food, adapted to the different specific food uses	Staple food, food for shortage periods, food diversification, tasty food with a nice texture, nutritional qualities, specific culinary use
	3.2. Crop variety that limits workload for food preparation	Easy to cook or mash
4. Sale	4.1. Crop variety that provides marketable products	High price on the local market, source of income for women
5. Other uses	5.1. Crop variety that provides other products for non-food uses	Fodder, building material
Non-material NCP		
6. Attachment	6.1. Crop varieties that makes farmers remember their father, and is part of their attachment to tradition	Father memory, attachment to tradition,
7. 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 for which seeds are available in the household, variety grown by everybody in the village

two different types of nodes represented the different sources and motivations, respectively, and where the ties represented the number of times farmers cited a given motivation for growing any variety that was obtained through a given seed source. Such a bipartite network can be represented as a table (Fig. 2), where the rows represent a given type of nodes (e.g. sources), the columns represent another type of node (motivations), and at row i and column j of the table one reads the number of times the source i has been cited for motivation j (here represented on a grey scale). This representation is quite convenient when considering small weighted networks.

(ii) Objective 2: understanding how motivations and seed sources varied by crop variety. We aimed to identify if the seed sources used by farmers and the associated motivations differed between varieties. This allowed us to bring a finer-grain discussion of the specifics of each variety and its contribution to the general aggregated pattern observed for the three crop species. This division according to varieties was more relevant than according to species, because the different varieties for a given species can be linked to very different NCPs. For instance, for both cowpea and peanut, some varieties are dedicated to fodder and other to grain production. We analyzed the "varieties x [motivations, seed sources]" tripartite network (network 2). The ties between sources and varieties represented the number of times each variety was obtained by farmers from a given source, and the ties between varieties and motivation represented the number of times farmers cited the different motivation for each variety (Fig. 3). This tripartite network is represented by two tables sharing the same rows.

(iii) Objective 3: Identify household profiles based on the combination of motivations and seed sources. In order to identify different household profiles of combined seed sourcing and motivations, we analyzed the "household x [motivation, seed sources]" weighted tripartite network (network 3). The ties between households and motivations represented the number of times each motivation was cited by farmers in that household, and the ties between household and seed sources represented the number of times farmers reported getting seeds for these sources (See SI 1 for the network matrix graphical display).

2.5. A probabilistic approach to analyze the networks

When analyzing a network, it is important to get a mesoscopic view of its structure (or topology), thus highlighting any patterns and/or identifying the role played by households/individuals, motivations and seed sources. The probabilistic approach assumes that the networks at stake are the realization of unspecified probabilistic distributions. Using the probabilistic framework ensures theoretical properties of the inferred quantities and thus the resulting decisions. In this paper, we employed latent block modeling (LBM) adapted to bipartite networks and its extensions to tripartite weighted networks (and more complex networks) by Bar-Hen et al. (2020).

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

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

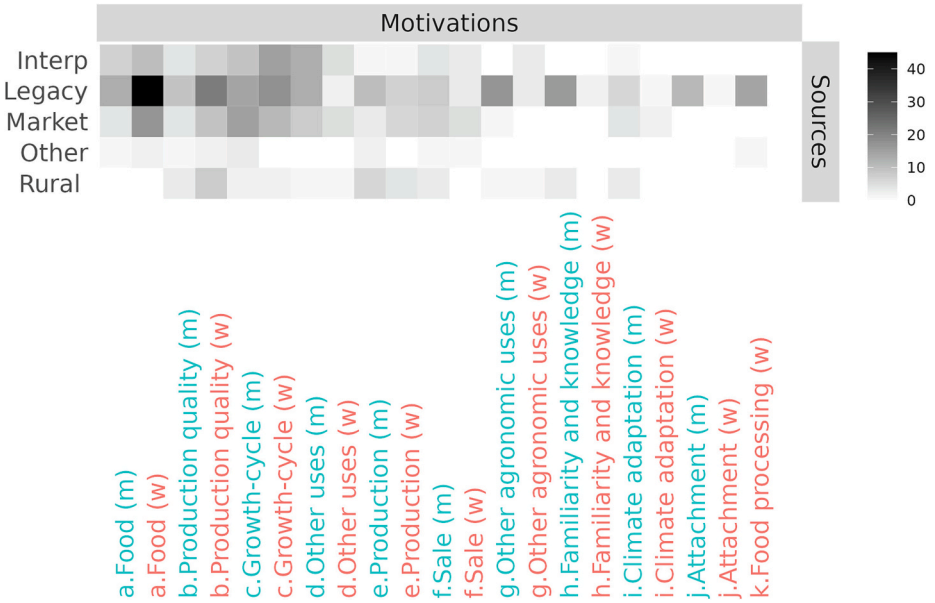

Fig. 2. Weighted bipartite network matrix [Source x Motivations] on all species. Represented as a table. Motivations cited by women are in red while the ones cited by men are in blue. Grey cells represent the ties between sources and motivations, that is the number of times farmers cited a given motivation for growing any variety that was obtained through a given seed source. The darker the box (i,j) the more the source of supply is associated with motivation j. As an example, 40 women declared that they got their varieties used for food from inheritance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

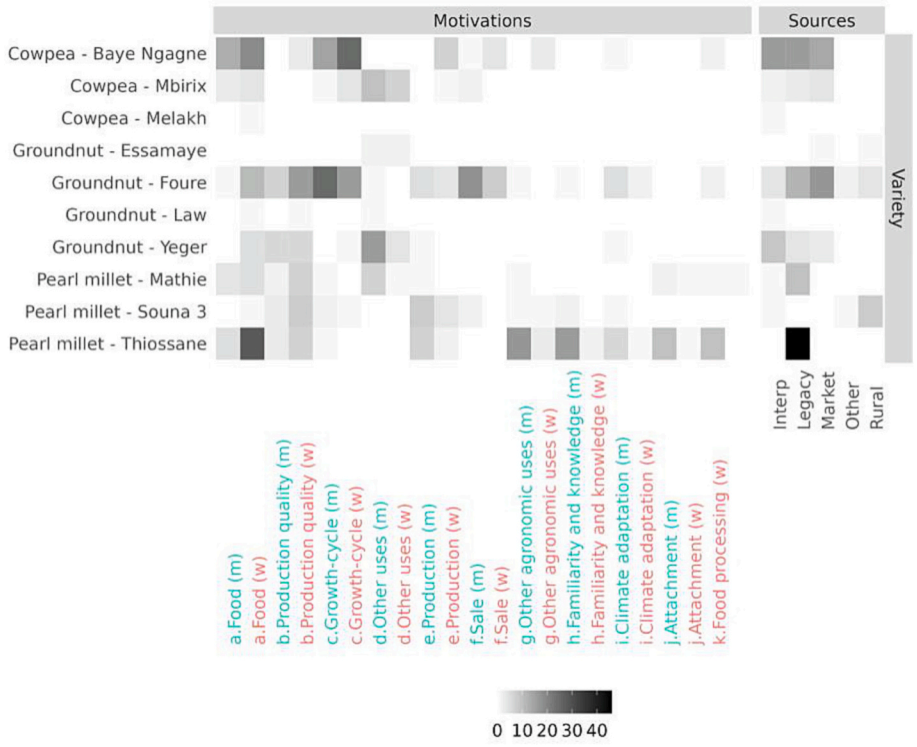

Fig. 3. Tripartie network matrix Varieties x [motivations, seed sources]. Motivations cited by women are in red while the ones cited by men are in blue. Grey cell represents ties between sources and varieties, and between varieties and motivations. The darker the box (i,j) the more the source of supply is associated with motivation j. As an example, 28 women declared that they used the variety of mil Thiossane for food. All the interviewed people declare that they obtained Thiossane by legacy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Motivation and seed sources according to gender

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

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

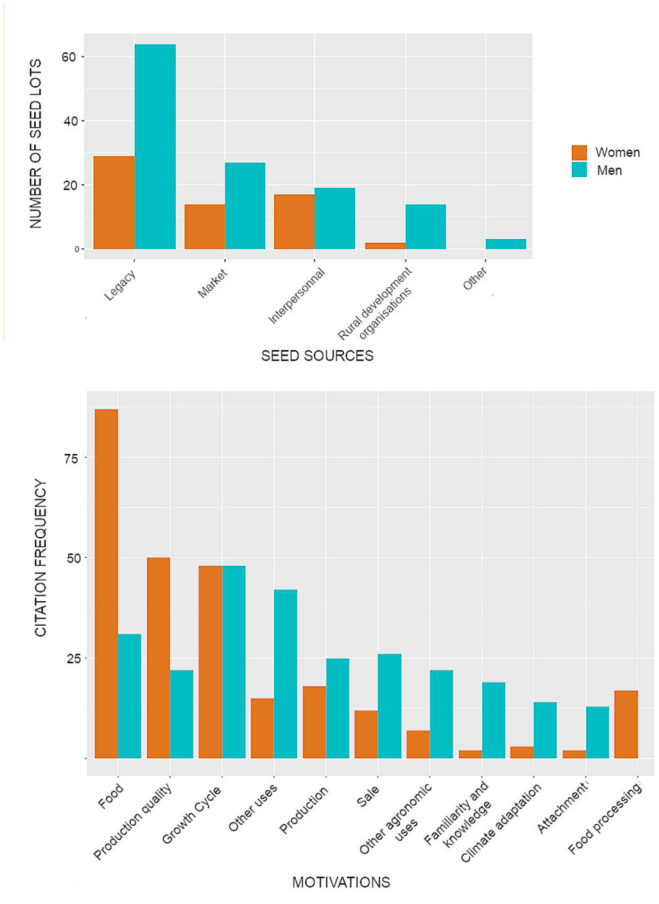

Fig. 4. Top: Number of seed-lots obtained by men ($n = 127$) and women ($n = 62$) farmers from the five categories of seed sources. Bottom: number of citations per category of motivation by women ($N = 47$) and men ($N = 44$).

motivations related to food processing (e.g. easiness to cook and process the seeds).

3.2. Relationship between channels of seed sourcing and motivations

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

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

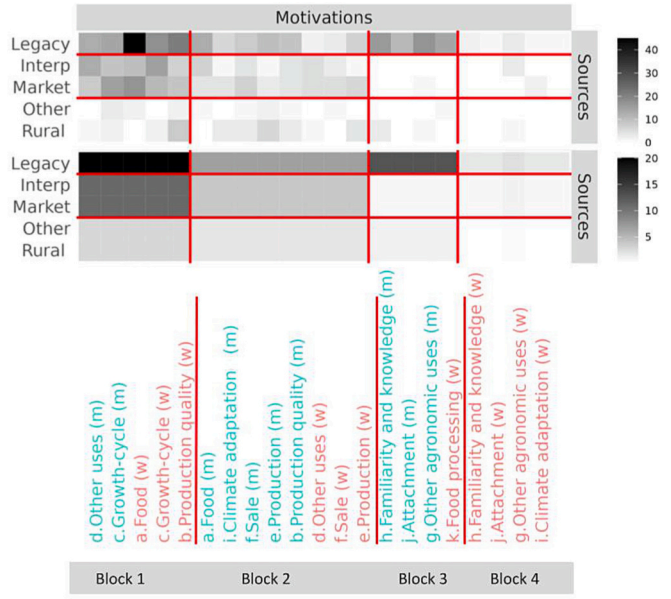

Fig. 5. Network Sources-Motivations matrices on data aggregated for all the varieties of the three species. A. (top): reordered table following the inferred blocks. B. (bottom): mean number of interactions for each pair of blocks. For instance, on average, 20 women declared having inherited seeds they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

The results of the LBM of the tripartite network variety X [motivations, seed sources] brought a more detailed understanding of the observations described for the aggregated data (Fig. 6). They highlighted that the different varieties of pearl millet, groundnut, and cowpea were sourced through different channels and associated with different motivations. The pearl millet variety *Thiossane* was clearly distinguished from the rest of the varieties (Block 1), because it was exclusively obtained by farmers through legacy, and it is the only variety men associated with the motivations related to familiarity, attachment, food production, other agronomic motivations (e.g. soil adaptation, low fertility requirement), climate adaptation, and production (quantity and quality). This particular pattern for *Thiossane* variety probably explains the higher prevalence of seed sourcing through legacy observed for men in the general analysis on aggregated data presented above (Fig. 5). Women associated *Thiossane* primarily with motivations related to food, and then to the quality of production and to food processing. *Thiossane* is a local traditional variety cultivated by all households for self-consumption as a staple food crop. It is mainly managed by men and transmitted from fathers to their sons (pers. obs.).

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

Third, the pearl millet variety *Souna 3* was distinguished from the rest of the varieties (Block 3), because it was the only one sourced from rural development organizations (associations) or other actors (official seed producers). Indeed, this variety was bred by the national research center and released at the end the 1970's. It is rarely cultivated, and was only present in one of the villages surveyed. It was only associated with

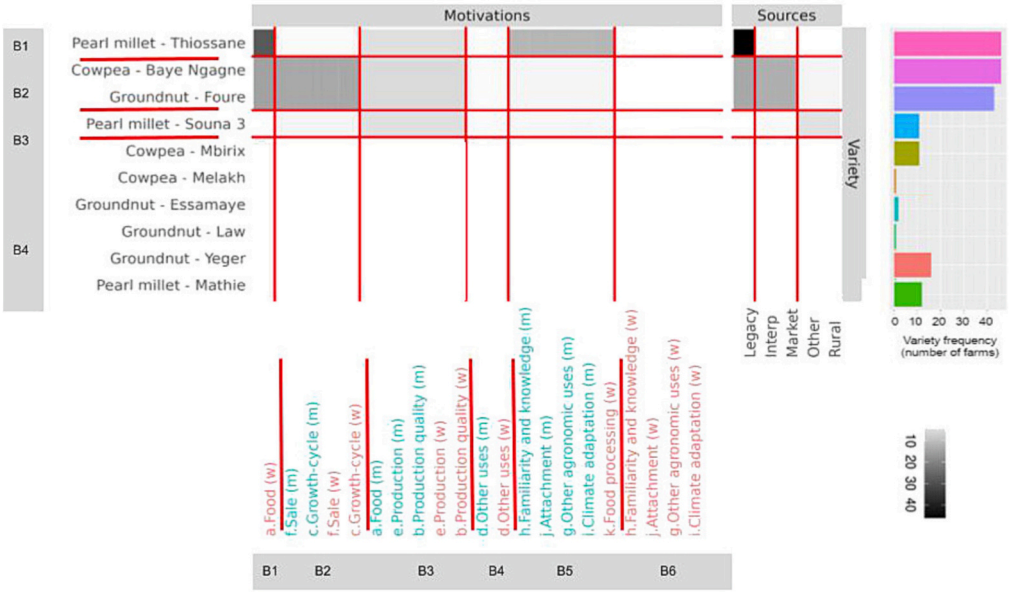

Fig. 6. Results of multi-stakeholder LBMs on the matrix « varieties X sources; motivations » for the three species (right), and frequency of each variety in the village (left, number of households cultivating each variety).

motivations related to food and the quality of production (produces a large amount of flour) by both men and women.

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

3.3. Identifying profiles of households depending on the combined seed sources and motivations

The analysis of the multipartite network of Households x [sources; motivations] with the three target species taken separately indicated that the optimal number of blocks calculated through the penalized likelihood criterion (ICL) was one or two (ICL of −1602 for one block versus −1615 for two blocks). In order to highlight the different household strategy, we retained the LBM results with two blocks of households (See figure in SI 1). The main difference between the two blocks was that the first one groups together households that cited a broader range of motivations for millet and groundnut, and to a lesser extent, a larger number of seed sources than the second Block (Fig. 7). This was probably related to the fact that the households in Block 1 grew on average more varieties (4.8, sd = 1.4) than in Block 2 (3.2, sd = 0.9). No particular differences in the socio-economic status of households belonging to each group were detected.

4. Discussion

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

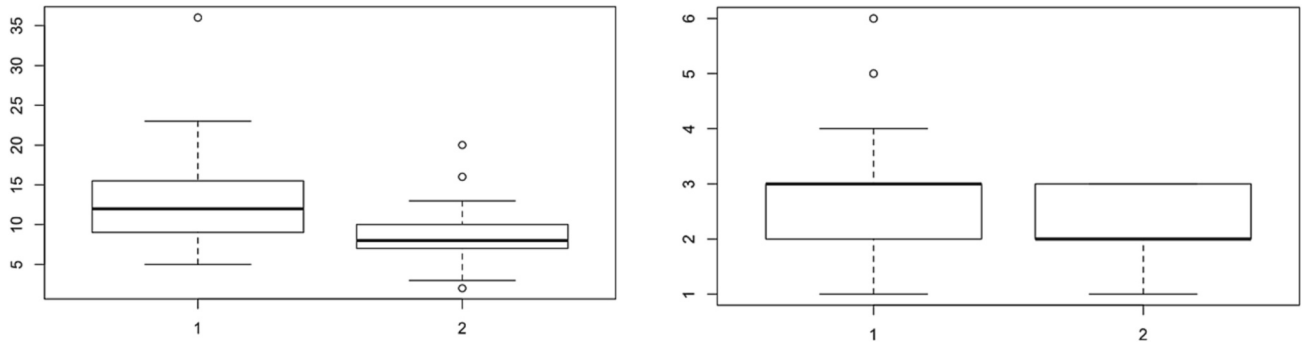

Fig. 7. left: Mean number of motivations cited per household and its standard deviation (Y axis) for each LBM block (X axis). Right: Mean number of seed sources cited per household and its standard deviation (Y axis) for each LBM block (X axis).

with a reflection on the limitations of the study and future research directions.

4.1. Farmers combine a range of seed sourcing channels to secure their access to NCPs necessary for their livelihoods

We found that Sereer farmers did not rely on a unique type of seed sourcing channel, but rather mobilized a mix of different channels to meet a range of NCPs that are key for their livelihoods and well-being. Farmers rarely obtained seeds through the official channels, and mainly relied on legacy, exchange through peer-to-peer relationships, and commercial relationships with different types of seed sellers at local markets or shops. These results align with previous studies in Africa showing that the so-called "formal" or official seed dissemination channels are rarely mobilized by farmers (McGuire and Sperling, 2016). Reasons cited in the literature are mainly the high cost of buying certified seeds through the official channels, and that the benefit expected in terms of increased yield is frequently not attained by farmers due to sub-optimal growing conditions (e.g. limited access to fertilizer, water stress). Supply of seeds through formal channels can also be constrained by supplier interests and preferences. For example, suppliers tend to focus on just a few crops and varieties, they may sell at locations that are far away or not readily accessible, and they may price seeds too high for many smallholder farmers. Further, as in other smallholder agricultural systems (Almekinders and Louwaars, 2002), we observed that varieties that would have been initially released by the official crop breeding system were frequently obtained by farmers through peer-to-peer seed circulation and through local markets, which is a common pattern for agricultural innovations to spread (e.g. Röling, 2009; Teeken et al., 2012). This was possible because the varieties released by the state crop breeding system were not hybrid ones. However, even if the official distribution channels represent a very small proportion of the seed sources documented in this study, their importance and contribution to the diversity of crops grown by farmers is potentially significant. Finally, the low prevalence of the State distribution channels in this study may not be representative of the situation in other places in Senegal (IPAR, 2015), illustrating the importance of acknowledging the local context when considering smallholder systems.

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

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

4.2. Gender discrepancies in source and motivations and differences between varieties

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

First of all, this study showed that women relied on a more limited pool of sources for seeds than men. Men generally cited a wider range of seed sources than women for the three grain crop species. Interestingly, women mentioned the market and legacy as seed sources less frequently than men. Men cited rural organizations while women did not, suggesting that women have limited access to this source. Several processes may explain the gender differences observed in seed sources. First, men in the Sereer society are the ones in charge of pearl millet cultivation and seed management, and they traditionally get their seed through inheritance from their father, which probably explains the higher importance of this seed source for men as compared to women. Second, men dedicate more time than women to social interactions outside the household, while women have a considerably larger workload in the home. Men thus have more opportunities to connect to a larger range of seed providers than women. Men also possess more money than women, who mostly rely on their husbands for resources, which may explain the differential access to the market. As such, non-monetary seed sourcing channels such as peer-to-peer gifts or exchanges appear particularly pivotal for women to access seeds. Previous research in Africa supports these findings, showing how women rely mostly on their own seeds, personal connections, or local markets, rather than extension services, seed companies, or farmers groups (e.g., Marimo et al., 2021; McGuire and Sperling, 2016). While social factors may influence where men and women source seeds, there is evidence from other studies that policies and programs that empower women or put them in decision-making positions can encourage more agrobiodiversity (e.g. Assefa et al., 2022; Valencia et al., 2021).

Men and women also perceived different NCPs in relation to the crop varieties. For instance, the millet landrace *Thiossane* was associated primarily with food uses by women, and with motivations related to familiarity and attachment or agronomic uses by men. Indeed, *Thiossane* is a men's crop in the Sereer society, transmitted from a father to his sons, creating a strong cultural attachment to the crop not seen among the women. Conversely, women are in charge of food preparation, which explains the importance they place on these motivations, which were also observed for the other crop species. This corroborates other studies that have found gendered rationale for crop choice, although these motivations vary by cultural and geographical context (Nordhagen et al., 2021; Sari et al., 2020; Oakley and Momsen, 2005). For instance, one study in Southeast Sulawesi found that men selected timber and fruit trees for shade based on economic benefits, while women cited production for household needs (Sari et al., 2020). Conversely, in Papua New Guinea, women tended to be more motivated by marketing potential, and men by tradition and status (Nordhagen et al., 2021). That said, the literature connecting gender and NCPs (here, the ecosystem services term is used) in general is very limited (Yang et al., 2018).

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

4.3. Implications for the resilience of agricultural systems

Our results showed that different seed channels are complementary from farmers' perspectives, as they allow them to access different crop varieties that provide different NCPs. For instance, legacy allows farmers to obtain seeds from the local traditional *Thiossane* millet landrace associated with tradition, heritage, and identity (in addition to agronomic and use benefits), while commercial channels provide them with the *Foure* groundnut variety related to marketability and agronomic properties/adaptation (material and regulating NCP). We also observe redundancy as farmers mobilized different seed sources to get varieties associated with key NCPs for their livelihoods. For instance, cowpea variety *Baye ngagne*, which was pivotal for both women's income and food provision, was obtained through a range of seed sources. This redundancy can improve the resilience of seed provisioning, providing alternatives when seeds are no longer available from one source (Matsushita et al., 2016; Massawe et al., 2016). Diversifying seed sources as a possible strategy to mitigate perturbations appears to be a practice shared by most households in this study, who demonstrated very similar seed sourcing practices and cited similar motivations.

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

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

4.4. Limitations and future research directions

The examination of seed sources, crop choice, and associated NCPs is still an active field of research. As such, there are several directions to take this work further, and limitations in the current study. For one, while seeds may originate from a variety of sources and due to a suite of motivations, how those differ between households appeared to be fairly limited in this study. The main difference between households was for the number of motivations, and to a lesser extent the number of seed sources, that were reported for the three species at the household level. Future investigations would be required to understand the factors explaining the inter-household differences in the number of motivations and seed sources cited. It is also worth noting that we limited our analysis to what was elicited by farmers, and so in some cases motivations for both the variety and for the source may be highly intermingled and thus difficult to tease apart.

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

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

5. Conclusion

This study illustrates how representing the interactions between crop varieties (biological entities), seed sources (social entities), and NCPs in the form of SEN networks opens new ways for analyzing such complex systems of interactions. Analyzing these relationships brings new insights about the resilience of farmers by identifying how vulnerable is the provision of the different NCPs to disruptions that impact particular seed sources. Our results showed that the maintenance of a range of NCPs, which are instrumental for households' resilience, relies not exclusively on interpersonal seed exchanges or official seed diffusion channels, but on a diversity of seed sources that allow farmers to get a range of crops, and which are complementary. Our study therefore indicates that development initiatives aimed at centralizing and structuring seed diffusion often don't match with smallholder needs and may instead compromise their resilience. Instead, the coexistence of different types of seed sources and their interactions should be further supported by development policies to enhance smallholder resilience to global changes.

Declaration of Competing Interest

Vanesse Labeyrie reports financial support was provided by Agropolis Foundation. Vanesse Labeyrie reports a relationship with National Socio-Environmental Synthesis Center that includes: travel reimbursement.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103726.

References

Almekinders, C.J., Louwaars, N.P., 2002. The importance of the farmers' seed systems in a functional national seed sector. J. New Seeds 4, 15–33.

Altieri, M.A., Nicholls, C.I., 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Climate Change 140, 33–45.

Assefa, W., Kewessa, G., Datiko, D., 2022. Agrobiodiversity and gender: the role of women in farm diversification among smallholder farmers in Sinana district, Southeastern Ethiopia. Biodiversity and Conservation 1–20.

Bar-Hen, A., Barbillon, P., Donnet, S., 2020. Block Models for Generalized Multipartite Networks: Applications in Ecology and Ethnobiology. Statistical Modelling.

Benoit-Cattin, M., Faye, J., 1982. L'exploitation agricole familiale en Afrique soudano-sahélienne (PUF).

Berg, T., 2009. Landraces and folk varieties: a conceptual reappraisal of terminology. Euphytica 166, 423–430.

Bezner Kerr, R., 2013. Seed struggles and food sovereignty in northern Malawi. J. Peasant Stud. 40 (5), 867–897.

Bhattarai, B., Beilin, R., Ford, R., 2015. Gender, agrobiodiversity, and climate change: a study of adaptation practices in the Nepal Himalayas. World Dev. 70, 122–132.

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

Cabell, J.F., Oelofse, M., 2012. An indicator framework for assessing agroecosystem resilience. Ecol. Soc. 17.

Calvet-Mir, L., Calvet-Mir, M., Molina, J.L., Reyes-García, V., 2012. Seed exchange as an agrobiodiversity conservation mechanism. A case study in Vall Fosca, Catalan Pyrenees, Iberian Peninsula. Ecol. Soc. 17 (1).

Carrington, P.J., Scott, J., Wasserman, S. (Eds.), 2005. Models and Methods in Social Network Analysis, vol. 28. Cambridge University Press.

Chiquet, J., Donnet, S., Barbillon, P., 2021. sbm: Stochastic Blockmodels [Online]. Available: https://cran.r-project.org/package=sbm.

Cobelli, O., Faye, N.F., Beaurepaire, S., Raimond, C., Labeyrie, V., 2023. Modes de gestion de la diversité cultivée par les paysans dans le bassin arachidier au Sénégal : la coexistence comme nouvelle normalité ? Droits et Cultures.

Croft, M.M., Marshall, M.I., Odendo, M., Ndinya, C., Ondego, N.N., Obura, P., Hallett, S. G., 2018. Formal and informal seed systems in Kenya: supporting indigenous vegetable seed quality. J. Dev. Stud. 54, 758–775.

Dee, L.E., Thompson, R., Massol, F., Guerrero, A., Bohan, D.A., 2017. Do social–ecological syndromes predict outcomes for ecosystem services?–A reply to Bodin et al. Trends Ecol 32 (8), 549–552.

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

Delaunay, V., Douillot, L., Diallo, A., Dione, D., Trape, J.-F., Medianikov, O., Raoult, D., Sokhna, C., 2013. Profile: the Niakhar health and demographic surveillance system. Int. J. Epidemiol. 42, 1002–1011.

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

Denton, F., 2002. Climate change vulnerability, impacts, and adaptation: why does gender matter? Gend. Dev. 10, 10–20.

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

Felipe-Lucia, M.R., Guerrero, A.M., Alexander, S.M., Ashander, J., Baggio, J.A., Barnes, M.L., Bodin, Ö., Bonn, A., Fortin, M.-J., Friedman, R.S., 2022. Conceptualizing ecosystem services using social–ecological networks. Trends Ecol. Evol. 37 (3), 211–222.

Ficiciyan, A., Loos, J., Sievers-Glotzbach, S., Tscharntke, T., 2018. More than yield: ecosystem services of traditional versus modern crop varieties revisited. Sustainability 10 (8), 2834.

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

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

Helicke, N.A., 2015. Seed exchange networks and food system resilience in the United States. J. Environ. Stud. Sci. 5, 636–649.

Hirons, M., Comberti, C., Dunford, R., 2016. Valuing cultural ecosystem services. Annu. Rev. Environ. Resour. 41, 545–574.

Hlatshwayo, S.I., Modi, A.T., Hlahla, S., Ngidi, M., Mabhaudhi, T., 2021. Usefulness of seed systems for reviving smallholder agriculture: a south African perspective. Afr. J. Food Agric. Nutr. Dev. 21, 17581–17603.

Huyer, S., 2016. Closing the Gender Gap in Agriculture. New Delhi, India, SAGE Publications Sage India.

IPAR, Initiative Prospective Agricole Rurale, 2015. Subventions des intrants agricoles au Sénégal : Controverses et Réalités. Rapport annuel sur l'état de l'agriculture et du monde rural au Sénégal.

Jackson, L., van Noordwijk, M., Bengtsson, J., Foster, W., Lipper, L., Pulleman, M., Said, M., Snaddon, J., Vodouhe, R., 2010. Biodiversity and agricultural sustainagility: from assessment to adaptive management. Current Opiion on. Environmental Sustainability 2, 80–87.

Jost, C., Kyazze, F., Naab, J., Neelormi, S., Kinyangi, J., Zougmore, R., Aggarwal, P., Bhatta, G., Chaudhury, M., Tapio-Bistrom, M.-L., 2016. Understanding gender dimensions of agriculture and climate change in smallholder farming communities. Clim. Dev. 8, 133–144.

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

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

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

Kremen, C., Merenlender, A.M., 2018. Landscapes that work for biodiversity and people. Science 362, eaau6020.

Labeyrie, V., Deu, M., Barnaud, A., Calatayud, C., Buiron, M., Wambugu, P., Manel, S., Glaszmann, J.-C., Leclerc, C., 2014. Influence of ethnolinguistic diversity on the sorghum genetic patterns in subsistence farming systems in eastern Kenya. PLoS One 9, e92178.

Louwaars, N.P., De Boef, W.S., 2012. Integrated seed sector development in Africa: a conceptual framework for creating coherence between practices, programs, and policies. J. Crop Improv. 26, 39–59.

Louwaars, N.P., Manicad, G., 2022. Seed systems resilience—an overview. Seeds 1 (4), 340–356.

Marimo, P., Otieno, G., Njuguna-Mungai, E., Vernooy, R., Halewood, M., Fadda, C., Mulumba, J.W., Nyamongo, D.O., Mollel, M., 2021. The role of gender and institutional dynamics in adapting seed systems to climate change: case studies from Kenya. Tanzania and Uganda. Agriculture 11, 840.

Martin, A.R., Cadotte, M.W., Isaac, M.E., Milla, R., Vile, D., Violle, C., 2019. Regional and global shifts in crop diversity through the Anthropocene. PLoS One 14.

Massawe, F., Mayes, S., Cheng, A., 2016. Crop diversity: an unexploited treasure trove for food security. Trends Plant Sci. 21 (5), 365–368.

Matsushita, K., Yamane, F., Asano, K., 2016. Linkage between crop diversity and agro-ecosystem resilience: nonmonotonic agricultural response under alternate regimes. Ecol. Econ. 126, 23–31.

McGuire, S., Sperling, L., 2013. Making seed systems more resilient to stress. Global Environmantal Change 23, 644–653.

McGuire, S., Sperling, L., 2016. Seed systems smallholder farmers use. Food Security 8, 179–195.

Morton, J.F., 2007. The impact of climate change on smallholder and subsistence agriculture. Procedings of the National Academy of Sciences 104, 19680–19685.

Nordhagen, S., Pascual, U., Drucker, A.G., 2021. Gendered differences in crop diversity choices: a case study from Papua New Guinea. World Dev. 137, 105134.

Oakley, E., Momsen, J.H., 2005. Gender and agrobiodiversity: a case study from Bangladesh. Geogr. J. 171 (3), 195–208.

Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., Watson, R.T., Başak, Dessane E., Islar, M., Kelemen, E., 2017. Valuing nature's contributions to people: the IPBES approach. Curr. Opin. Environ. Sustain. 26, 7–16.

Renard, D., Tilman, D., 2021. Cultivate biodiversity to harvest food security and sustainability. Curr. Biol. 31 (19), R1154–R1158.

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., Chookolingo, B., 2018. How much of the world's food do smallholders produce? Global Food Security 17, 64–72.

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

Röling, N., 2009. Pathways for impact: scientists' different perspectives on agricultural innovation. Int. J. Agric. Sustain. 7 (2), 83–94.

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

Sayles, J.S., Garcia, M.M., Hamilton, M., Alexander, S.M., Baggio, J.A., Fischer, A.P., Ingold, K., Meredith, G.R., Pittman, J., 2019. Social-ecological network analysis for sustainability sciences: a systematic review and innovative research agenda for the future. Environ. Res. Lett. 14 (9), 093003.

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

Steenkamp, J.B., Van Trijp, H., 1997. Attribute elicitation in marketing research: a comparison of three procedures. Mark. Lett. 8 (2), 153–165.

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

Tadesse, Y., Almekinders, C.J., Schulte, R.P., Struik, P.C., 2017. Tracing the seed: seed diffusion of improved potato varieties through farmers'networks in Chencha, Ethiopia. Exp. Agric. 53, 481–496.

Teeken, B., Nuijten, E., Temudo, M.P., Okry, F., Mokuwa, A., Struik, P.C., Richards, P., 2012. Maintaining or abandoning African rice: lessons for understanding processes of seed innovation. Hum. Ecol. 40 (6), 879–892.

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

Valencia, V., Wittman, H., Jones, A.D., Blesh, J., 2021. Public policies for agricultural diversification: implications for gender equity. Frontiers in Sustainable Food Systems 5, 718449. https://doi.org/10.3389/fsufs.

van Niekerk, J., Wynberg, R., 2017. Traditional seed and exchange systems cement social relations and provide a safety net: a case study from KwaZulu-Natal, South Africa. Agroecol. Sustain. Food Syst. 41, 1099–1123.

Velásquez-Milla, D., Casas, A., Torres-Guevara, J., Cruz-Soriano, A., 2011. Ecological and socio-cultural factors influencing in situ conservation of crop diversity by traditional Andean households in Peru. J. Ethnobiol. Ethnomed. 7 (1), 1–20.

Yang, Y.E., Passarelli, S., Lovell, R.J., Ringler, C., 2018. Gendered perspectives of ecosystem services: a systematic review. Ecosystem Services 31, 58–67.