The role of farmers' networks in sourcing planting material and information in a context of agroforestry transition in Madagascar

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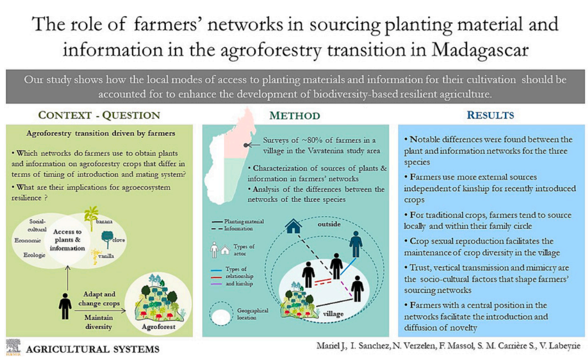
Juliette Mariel[a,b,*], Isabelle Sanchez[c], Nicolas Verzelen[c], François Massol[d], Stéphanie M. Carrière[e], Vanesse Labeyrie[a,b]

[a] CIRAD, UMR SENS, 34398 Montpellier, France
[b] SENS, CIRAD, IRD, Univ Paul Valery Montpellier 3, Univ Montpellier, Montpellier, France
[c] Univ. Montpellier, INRAE, Institut Agro, UMR 729 MISTEA, Montpellier, France
[d] Univ. Lille, CNRS, Inserm, CHU Lille, Institut Pasteur de Lille, U1019 - UMR 9017 - CIIL - Center for Infection and Immunity of Lille, F-59000 Lille, France
[e] SENS, IRD, CIRAD, Univ Paul Valery Montpellier 3, Univ Montpellier, Montpellier, France

HIGHLIGHTS

- Access to seedlings and information plays a crucial role in enabling farmers to adapt their crops to ongoing changes.
- Sources of seedlings and information for 3 agroforestry crops with different histories and mating systems are compared.
- Sources used by farmers differed significantly, notably the proportion and types of kinship ties and their location.
- Socio-cultural factors shape both farmers' sourcing networks and resilience mechanisms in the agroforestry transition.
- Local mechanisms behind farmers' access to agrobiodiversity should be considered in development and adaptation programs.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Crop diversity contributes to the resilience of agroecosystems by enhancing their capacity to adapt to perturbations. Farmers' access to crop planting material and information required for their, is crucial as it allows farmers to maintain a high level of crop diversity and adapt their crop portfolio to the changing social-ecological context. Despite their presumed importance for the resilience of small farms, the processes that influence farmers' access to the planting material of new crops and the information associated have rarely been studied.
OBJECTIVE: Our aim was to analyze the social networks that Betsimisaraka farmers in Madagascar use to access planting material and associated information. This would advance our understanding of the processes involved in the transformation of these agroecosystems into diversified agroforests that confer more resilience to local farming systems.
METHODS: We compare the networks of clove and vanilla, whose cultivation in the area expanded in recent decades, with the network of banana, a traditionally cultivated crop.

* Corresponding author at: Cirad Campus International de Baillarguet, Chemin de Baillarguet, 34980 Montferrier-sur-Lez, France.
E-mail address: juliette.mariel@cirad.fr (J. Mariel).

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We conducted an exhaustive survey of 98 households in a village on Madagascar's northeast coast to gather data on the farmers' access to clove, vanilla and banana planting material and information concerning their cultivation. We analyzed the differences and similarities between the three networks, in particular the types of relationship mobilized, the nature of kinship ties, and the geographical extent of networks.

RESULTS AND CONCLUSIONS: Our results show that the studied networks include both weak bridging ties over long distances that give the farmers access to crops that were rarely cultivated in the area until recently (vanilla), and strong local ties that facilitate farmers' access to crops that are broadly cultivated locally (clove and banana). Major differences were found in the nature of ties used by farmers to access planting material and relevant information for these different crops. The implications of the network characteristics observed for the resilience of the farming systems are discussed.

SIGNIFICANCE: Our study underlines the importance of taking local modes of access to crop diversity and associated information into consideration to enhance the development of biodiversity-based resilient agriculture. We recommend that the local social processes that drive this access should be fully integrated in development and adaptation programs.

1. Introduction

Family farming in tropical regions is currently facing major challenges to adapting to changes at both local scale (e.g. declining fertility) and global scale (e.g. climate change, fluctuating market price) (Mbow et al., 2014; Malard et al., 2014; Altieri and Nicholls, 2017). The resilience of agroecosystems, i.e. their capacity to deal with these changes while continuing to function (Cumming and Peterson, 2017), relies to a great extent on agrobiodiversity, particularly on crop diversity and the local knowledge associated with crop management (Qualset et al., 1995; Jackson et al., 2012). Changing and diversifying crops is a resilience strategy frequently used by farmers to adapt or transform their farming system (Lin, 2011; Labeyrie et al., 2021b). According to the redundancy principle, agroecosystem resilience can be achieved by replacing one crop species by another similar species or by adding new species with similar functions (Sterk et al., 2017). Another mechanism of resilience is in-depth transformation of agroecosystems by cultivating crops with new functions that are more appropriate in the context, for instance by replacing subsistence crops by cash crops.

The processes that condition farmers' access to new crops and to the information required for their management, i.e. agrobiodiversity, is an unexplored facet of the resilience of small farms. Theoretical and empirical studies have highlighted how patterns of social connectivity affect the resilience of social-ecological systems' by influencing access to key resources and innovations (Barnes et al., 2017). Several studies of agroecosystems have shown that farmers' connectivity affects their capacity to access innovations, and hence their resilience capacity (Tomich et al., 2011; Rockenbauch and Sakdapolrak, 2017), but few studies have examined how farmers' connectivity affects their access to agrobiodiversity, even though its key role in agroecosystem resilience is broadly acknowledged (Vandermeer et al., 2002).

Farmers' connectivity to sources of crops and associated information will be crucial for them to maintain diversity in their cropping systems and to continue to adapt their crop portfolios to respond to potential future changes (Coomes et al., 2015; Labeyrie et al., 2021a). This situation calls for a better understanding of the factors and processes that influence farmers' access to crops and associated information in a context of adaptation and transformation of agroecosystems (Janssen et al., 2006; Rockenbauch and Sakdapolrak, 2017).

An abundant literature on farmers' seed systems worldwide shows that a diversity of actors is involved in farmers' networks. Interpersonal relationships, and especially kinship ones, are a major source of planting material and information in the Global South (Pautasso et al., 2013; Coomes et al., 2015; McGuire and Sperling, 2016). The type of relationship and the characteristics of the actors involved have been found to affect the circulation of both seeds and information (Calvet-Mir and Salpeteur, 2016; Abizaid et al., 2016; Porcuna-Ferrer et al., 2023) and the introduction and adoption of innovations (Kiptot et al., 2006; Abebe et al., 2013), for example by migrant farmers (Isaac et al., 2014; Salpeteur et al., 2016). Consequently, the type of source is also known to affect the resilience of agroecosystems. For instance, positive relations are found between the crop diversity cultivated by the farmers and their relationship with external rural organizations (Isaac, 2012), or their propensity to give seeds to others farmers within the village (Abizaid et al., 2016). Others studies point out that farmers who play a central role in seed and knowledge exchange networks (i.e. farmers with high connectivity and wide range of connections) are the farmers with the highest crop diversity in their community (Calvet-Mir et al., 2012; Porcuna-Ferrer et al., 2023)). Furthermore, the connectivity between zones representing different social-ecological contexts is known to be instrumental in the introduction of new crops, and hence in the resilience of farming systems, as already reported for different types of resources and systems (Adger et al., 2002; Rockenbauch et al., 2019a; Mulyoutami et al., 2020). Certain studies in particular show that the adoption of innovations is favored by farmers who are connected with other geographically distant actors (Matouš et al., 2013; Wossen et al., 2013).

The aim of the present study was to analyze the sources used by farmers to access agrobiodiversity in a context of transformation of the farming systems into diversified agroforests, observed on the north-eastern coast of Madagascar (Mariel et al., 2022b). Agroforestry is widely recognized by the scientific community as an agrobiodiversity-based agriculture that improves the resilience of family farming in tropical region (Miller et al., 2020). Hence, our work addressed the links between resilience and social networks through a case study describing the network characteristics that have supported a resilient transformation of farming system. We focused on the networks used by farmers to source planting material for two crops that had undergone a boom in recent decades (clove and vanilla) and to source information related to their cultivation. We compared the network for clove and vanilla with that of banana, which has been cultivated in the area for centuries, to underline the particular networks' characteristics of new crops. Our comparative study of networks was based on the analyses of the types of actors involved and the geographical extent of ties, and the type of relationship involves, with a focus on the kinship relationships.

While the literature on crop circulation networks in general is abundant, to our knowledge, an analysis of network characteristics in the context of the introduction of new crops has not yet been conducted. Such an analysis will advance our understanding of the socio-cultural mechanisms involved in the circulation of planting material and information that have contributed to the development of smallholder farming systems with a higher agrobiodiversity.

2. Study site and research framework

2.1. Study site

The study was conducted in the Vavatenina district of the Analanjirofo region in Madagascar as it is an illustrative case study of a farmer-led agroforestry transition. We chose a village that had been the subject of an in-depth socio-economic, cultural and environmental study in the 1970s (Dandoy., 1973) and this historical study helped establish a frame of reference to describe changes in the situation that had occurred since then and to better understand what we observed in 2019, the year we conducted our survey. The Betsimisaraka population living in this region has long lived from subsistence shifting rice cultivation (locally referred to as *tavy*). During the colonial period (ended in 1960), Betsimisaraka farmers were forced to cultivate cash crops, mainly coffee but also clove and vanilla, depending on the regions. After the independence, the integration of Madagascar's economy into world markets has driven farmers' strategies, notably towards the abandonment of coffee and the development of clove, and more recently vanilla (Blanc-Pamard and Ruf, 1992; Danthu et al., 2022). While in the past, the cultivation of cash crops made monocropping mandatory (Maistre, 1955), many small-scale farmers nevertheless started cultivating these species in agroforests under varying levels of diversification (Petit, 1965; Blanc-Pamard and Ruf, 1992; Arimalala et al., 2019; Mariel et al., 2021).

Agroforests are present on the hills and are locally called *tsabo* (the term we use in the rest of this paper). In addition to cash crops, *tsabo* can contain rich agrobiodiversity (estimated at >51 species, Mariel et al., 2021) including fruit trees, timber trees, cassava, yams, and woody and herbaceous species that grow spontaneously (Arimalala et al., 2019). The fruits, wood or leaves of most of the species are consumed by the farm households themselves, and some also have agroecological functions (Mariel et al., 2021, 2022a). Many farmers also have a home garden, local name *ambany trano*, where they mainly grow food crops, fruit trees and keep small pigs or zebu. Like most *tsabo, ambany trano* are highly diversified and are important sources of agroforestry products. The planting and maintenance of trees and weeding operations in the *tsabo* are mainly done by men, while harvesting is a collective task done by the whole family.

2.2. Study of three agroforestry species

To describe the networks used by farmers to transform their cropping systems, we focused on two cash crops, clove (*Syzygium aromaticum*) and vanilla (*Vanilla planifolia*) and we compared these two networks with those used by farmers for banana (*Musa* sp.). In the history of agriculture in Madagascar, clove and vanilla were introduced by Europeans at the end of the XIX century and are currently the two main cash crops in the Analanjirofo region (Danthu et al., 2022). During the XX century, Betsimisaraka farmers from the Analanjirofo region have not adopted and developed these two cash crops in the same way. This has led to the differentiation of local agroecosystems specialized in the production of cloves and essential oil, as in the Vavatenina area, or in the cultivation of vanilla, as in the Mananara area (Danthu et al., 2014; Llopis et al., 2019). In contrast, banana has long been cultivated as a subsistence crop, it is deeply rooted in Betsimisaraka culture and has many uses (e.g. as an ingredient in different dishes, ornamental uses for ceremonies, as fertilizing material, and as a shade plant; Blanc-Pamard and Ruf, 1992; Mariel et al., 2022a, pers.obs.). Thus, compared with banana, clove and vanilla are substantially new crops to the region. In the studied village, Dandoy. (1973) described how the local economic context favored the plantation of clove trees, unlike vanilla, which remained “a crop in the process of being abandoned”. This historical situation enables to differentiate the novelty of the two species at the village scale: if the clove tree is now perceived by the farmers as a symbolic crop of Betsimisaraka culture, vanilla is identified as a recent crop which expansion is still ongoing. Thus, all farmers in the village we surveyed cultivate banana and clove in their agroforests, but not all farmers grow vanilla. Regarding biological aspects, the specificities of each of the three species influence farmer's cultivation and multiplication practices. In particular, the sexual reproduction of clove trees gives it a high rate of multiplication. Many farmers germinate clove seeds in small nurseries they set up in their own *tsabo* or simply transplant seedlings that result from natural germination of seeds that have fallen to the ground. The farmers in our study area only use cuttings to propagate vanilla plants, which are more sensitive and perishable planting material. Using cuttings results in a lower reproduction rate than seeds and can damage the mother plant. In the case of banana, the farmers recover the offshoots that grow at the foot of the mother plant.

2.3. Hypotheses

Based on field observations and surveys attesting to the rich diversity of plant species and cultivation practices used in the *tsabo* (agroforests), we hypothesized that farmers exploit different sources of planting material and of the information they need for the management of agroforestry species (Calvet-Mir et al., 2012; Isaac, 2012). We further hypothesized that the sources used by farmers to obtain planting material and associated information, and the way these resources circulate would differ between the three crops mainly depending on: (i) the timing of their introduction, and (ii) their reproduction system. We thus propose the following hypotheses.

First, we expected that recently introduced crops, like vanilla, were frequently sourced for the first time outside from the study village, in areas where such crops are more extensively cultivated. By contrast, we expected crops that have long been cultivated in the study area, like banana, to be mostly sourced within the village (Rockenbauch et al., 2019b).

Second, we expected these recently introduced crops to be sourced from a wider range of actors (other than peers), because local farmers may not produce enough planting material to supply other farmers. However, if sourced within the village, the recent crops would be more frequently sourced from expert farmers, as few farmers cultivate these crops to an extent that would enable them to supply planting material to others.

Third, as we linked the timing of introduction of a crop to its socio-cultural status, we also expected that more recently introduced crops would be less frequently sourced from relatives, as the circulation of these new crops is probably less socially constrained than that of traditional crops that have symbolic and social functions in the socio-ecological system (Thomas and Caillon, 2016).

All three hypotheses also applied to the way farmers sourced information about how to cultivate the species, as planting material exchange is often accompanied by information concerning the crop (Reyes-García et al., 2013; Keleman et al., 2009). In addition, previous studies indicate that, one the one hand, actors external to the local community (i.e. weak bridging ties) play a significant role in the introduction of information and practices related to new crops and, and on the other, that relatives or neighbors (i.e. local strong ties) have a crucial role in the sharing of knowledge within the community (Isaac, 2012). We thus expected that there is more knowledge sharing through kinship relationships and within the study village in the case of banana and clove than vanilla.

Finally, we expected that the system of propagation of crops (clonal or sexual) also influences where the farmers source their planting material (McGuire and Sperling, 2016). Clonal crops like vanilla and banana have a lower multiplication rate than crops propagated sexually, like clove. More abundant planting material is therefore available for clove within the village than for vanilla or banana. We would hence expect the farmers to obtain these crops more frequently from outside the village as the availability of clonal planting material may be limited.

3. Material and methods

3.1. Farmers: sampling and data collection

To obtain in-depth insights into the diversity of sources and to capture the complexity of farmers' management of agrobiodiversity, we conducted exhaustive sampling of 98 households in our study village. The fact no recent census has been made of the village population meant we were unable to assess the exact proportion of the households we surveyed, however, by counting the roofs of houses on a satellite image crossed with data provided by the village chief, we calculated our sample to represent between 75% and 82% of the total number of households estimated at between 120 and 130 households. We excluded households with no *tsabo* to manage from the sample. We interviewed the individual designated by the household as being the one who made most of the decisions concerning the management of agrobiodiversity in the *tsabo* that belonged to the household. The final sample of farmers comprised 18% women and 82% men distributed in three age categories: under 35 (3 women; 40 men), between 35 and 55 (3 women; 19 men), and over 55 (12 women; 21 men). This high proportion of sampled individuals at the village level makes it to possible to test the hypotheses described in the previous section and to draw statistical conclusions.

To better understand the role of surveyed farmers in supplying planting material and/or information, we recorded data on their social status in the village (e.g. local and customary authority, elder), the time they had spent outside the village (e.g. seasonal mobility, long-past migration), their involvement in a social group such as a farmers' organization or cultural association, their perception of what makes someone a vanilla and clove plantation expert, and who these experts are in the study village. To understand the proportions of the different types of relationships, we asked them who they trusted most, and to whom they would go to for agricultural advice. Informal discussions with farmers and key informants enabled us to obtain qualitative information on the social organization within the village and farmers' perceptions of local changes in agriculture, Betsimisaraka culture and social relationships, and the drivers of these changes.

3.2. Resources and sources: definitions, data collected and categorized

3.2.1. Resources

Planting material| To analyze the clove and vanilla planting material networks, we asked the farmers we interviewed to tell us where they got the first plant they had planted in their *tsabo*. The two networks were based on how the first farmers obtained these crops. In the case of banana, the network was based on the source of the two most recent landraces obtained by the farmers, as banana is often replanted when the plantation is being renewed, but not always using the same landrace. We also inquired what type of planting material was used, seed, seedling, cutting or offshoot (Fig. 1), as this influences the longevity, storage and ease of transport of planting material over long distances, and can consequently influence farmers' practices. For example, a clove seed is robust and easily transported (Fig. 1.A) whereas a banana offshoot is more fragile (tiny roots may be present) and heavy to transport. (Fig. 1.D).

Information| To characterize farmers' sources of information concerning the three crops, we decided to focus on specific knowledge domains, as asking for the sources of advice usually led to vague answers that could not be used to map the sources exploited by the farmers. We investigated the information networks by focusing on a specific agroecological characteristic of each of the three species the farmers considered in their decision to adopt and continue to cultivate them (Mariel et al., 2021). Information on cloves concerned the minimum and maximum age of clove trees to obtain a yield and the factors that may cause variation. Information on vanilla concerned the most suitable and beneficial tree to use as a tutor and the associated reasons. Information on banana concerned the other species on which the presence of banana had positive effects and what the effects are. Agroecological characteristics influence the way the farmers manage plant species in space and over time. We asked the farmers how they obtained information concerning the three species and by asking additional questions, we tried to find out if it involved **oral transmission** (i.e. being taught by somebody else), **mimicry** (i.e. observing what others do) or **experimentation** (i.e. learning by doing) (Reyes-García et al., 2009; Baggio and Hillis, 2018). In the present study, we considered the term "experimentation" to also apply to the case where farmers learn from what they test themselves by observing the results in their own *tsabo*. Consequently, this source of information was not included in the data we gathered to build the information networks.

3.2.2. Sources: ego and actor

The primary aim of the data collected on the sources of planting material and information was to differentiate between self-supply and experimentation (**source-ego**) from sources corresponding to an alter (**source-actor**). More precisely, source-ego of planting material corresponded to farmers who obtained it in their own *tsabo*, which meant it already contained clove trees, vanilla and/or banana plants that provided respectively, seeds, cuttings and/or offshoots. Unlike source-ego, source-actors of planting material and information thus corresponded to a circulation event and represented a tie in the network. To characterize the diversity of source-actors, we collected data concerning (i) the type of source-actors based on the nature of their relationship with the farmer, (ii) the nature of the kinship tie between the source-actor and the interviewee, when relevant, and (iii) the geographical location of the source-actor. We also documented the place of origin of the resource, i.e. *tsabo*, village, nursery or market.

Types of source-actor| To distinguish between social sources, we

Fig. 1. Pictures showing the different types of planting material (©Mariel): (A) seeds of clove tree and (B) clove seedlings in a farmer's nursery set up in his tsabo, (C) vanilla cuttings suspended from a bamboo stick, and (D) banana offshoot being transported in a basket.

first differentiated the peers: ***tantsaha***, i.e. men and women whose livelihoods mainly depend on agriculture, and **actors** other than peers (named **agri-actor**) who were not *tantsaha* but who were involved in the agricultural sector through their economic activities. The Malagasy use the term *fihavanana* to qualify the inter-individual relationship based on love, solidarity, trust and reciprocity. The system of rules and norms attached to *fihavanana* reflects how it is expressed more broadly in the way the Malagasy live (Sandron, 2008). In line with an emic approach, we based the categorization of source-actors on *fihavanana* and also because Gannon and Sandron (2006) suggested that it may constitute an obstacle to farming innovation. Thus, we asked the surveyed farmers about the nature of the relationships with the source-actor (*tantsaha* or agri-actor) on the basis of the presence or not of *fihavanana*. This led us to differentiate between *havagna* (**relative**) and *namagna* (**friend**), which are relationships based on *fihavanana*, from an acquaintance (but not close) *tantsaha* living in the study village (**villager**) or someone unknown *tantsaha* from outside the village (**unknown**). Apart from the geographical origin, the main difference between a villager and an unknown is that the farmer surveyed is able to name the source-actor originating from the village.

Type of kinship| When the source-actor was a relative, we asked for the exact affiliation and whether the person was still alive or not. Based on previous studies (Leclerc and Coppens d'Eeckenbrugge, 2011), we categorized the kinship tie between the farmer and the source-relative in nine types according to the gender of the farmer (men M and women W) and the type of blood affiliation (paternal, maternal, brother-sister, children) and added the category "husband" when the interview was with a widow. To help clarify the figures that present the results, we grouped under the same type of kinship, direct and indirect blood affiliation (e.g. the type "mother & kin" can correspond to a tie with the farmer's mother or the mother's parent).

Geographical location of the source-actor| To describe the spatial extent of the networks, we documented the geographical location of the source-actors on the basis of the administrative division of the country: region > district> commune> *fonkonatny* > village. We qualified the source-actors located outside the village as **external**, as well as the links between the farmers and the source-actor, and the ones located inside the village as **local**.

3.3. Analyses at the village level

For each of the three species studied, we described the way farmers acquire planting material and information based on calculations of the proportions of the various variables describing the sources (i.e. source-ego or source-actor, types of source-actor, types of kinship, geographical location). We characterized the diversity of sources in the circulation network of each species through three diversity indices (richness, Shannon and Pielou equitability). The calculation of these indices was based on the category of source-actor (i.e. relative, friend, villager, unknown and agri-actor) and their geographical location (i.e. local and external) and included both planting material and information. The calculations were conducted in R (R Core Team, 2021, version 4.3.1) with the package iNEXT (version 3.0.0). Richness (S) refers to the number of types of source, Shannon (H) and Pielou (J) indices describe richness considering the size of the sample (i.e. the abundance of each type of source) (Borcard et al., 2011). The Shannon index increases logarithmically with S and its values vary between 0 (one single type of source) and *log(Smax)* (Smax: maximum value of richness). Thus, the Shannon index gives more weight to rare sources of planting material and information in the network concerned. The Pielou index measures equitability between the different types of source within the network, i.e. it shows whether each type of source is used equally or very unevenly by the farmer being interviewed. Pielou index values range from 0 (one type of source is dominant) to 1 (all the sources are equally abundant).

We conducted statistical tests to evaluate significant differences in the proportions of the different categories of sources (i.e. source-ego/source-actor, types based on *fihavanana*, types based on the nature of the kinship and on the geographical location) between clove and vanilla, respectively, for planting material and information networks and between each of these two species and banana, for planting material and information networks, respectively. Depending on the number of acquisitions in each source category and the number of types in each category, we applied either a Fisher test or a χ^2 test. These tests are especially suitable for such comparisons and, importantly, do not rely on any data-distribution assumptions.

After discarding data on self-supply and experimentation (source-ego), the circulation networks of each species were visualized using the open source software GEPHI (https://gephi.org/). The nodes and the ties in the networks were first distributed using "Fruchterman Reingold" spatialization and second, we manually moved the nodes corresponding to external sources away according to a distance that reflected the different geographical scales. The thickness of the arrow shows the coupling of the two resources, i.e. when the planting material and the information come from the same source and circulate through the same tie. We calculated the network density and the out-degree of the farmers on directed networks based on both planting material and information acquisition, by using functions in the package igraph (version 1.2.7) in R (R Core Team, 2021, version 4.3.1).

4. Results

4.1. Comparison of clove and vanilla

4.1.1. Comparison of the sources of information

Relative to the total number of information acquisitions reported, the proportion of information obtained through experimentation (i.e. source-ego; Fig. 2) differed considerably between the two species, with 61% in the case of clove and only 8% in the case of vanilla (p-value = 3.98e-13; Table 1). Considering the acquisition of information involving source-actors, oral transmission dominated the circulation networks of both clove and vanilla (respectively 62% and 67%) compared with mimicry (respectively 38% and 33%).

Significant differences in the proportions of the different categories of actor-source were found between the clove and the vanilla circulation networks (p-value = 0.0351). The main category of relationship in the clove network was "relatives" (57%) followed by "villagers" (35%), while in the vanilla network, it was "villager" (34%), followed by "relatives" (32%) (Fig. 2). The "friend" and "unknown" categories accounted for a much smaller proportion of connections in the clove network (respectively 5% and 3%) than in the vanilla network (18% and 14%). Two "agri-actors", corresponding to employer in the vanilla plantations and the CSA (Agricultural Service Center), were observed for vanilla but not for clove.

The nature of kinship ties between farmers and actor-sources did not differ significantly between vanilla and clove (p-value = 0.2027). Whatever the gender of the farmer, clove- and vanilla-related information mainly originated from the farmer's father or kin (respectively 85% and 65%). The vanilla network had a higher proportion of sources corresponding to farmer's mother or kin (25%) than the clove network (10%).

The geographical location of the source-actors was statistically linked to the nature of the species (p-value = 0.0401). The two networks in Fig. 3 show that the clove network had fewer external source-actors and covered a smaller geographical area (three villages in the Vavatenina commune and two villages outside Vavatenina district) than the vanilla network which comprised 14 source-actors in the Vavatenina commune, six in Vavatenina district and nine in Mananara (outside Vavatenina district).

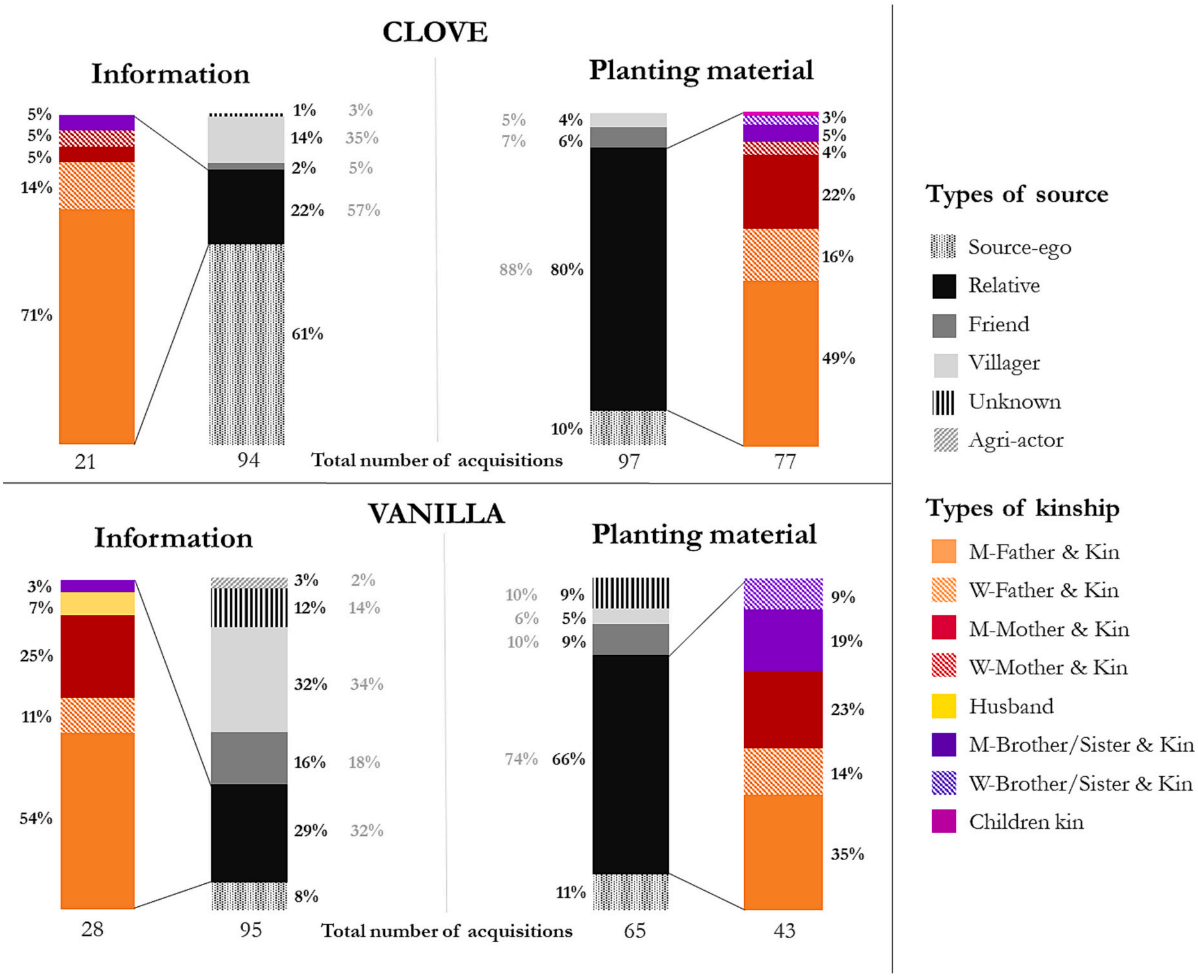

Fig. 2. Proportions of the different types of information sources and sources of planting material in the case of clove (upper panel) and vanilla (lower panel). Percentages in black were calculated relative to the total number of acquisitions, those in grey, relative to the total number of source-actors (i.e. the number of source-ego subtracted from the total number of acquisitions). The proportion of the kinship category "children kin" in the source of clove planting material was 1%.

Table 1
Results of the Fisher and χ^2 tests applied separately to sources of information and sources of planting material, and to test independence between the type of species (clove, vanilla, banana) and several variables characterizing the sources (i.e. ego or actor, type of actor, type of kinship and geographical location of the source-actor). The choice of test applied depended on the size of the sample. Levels of statistical significance are: $*P < 0.05$, $**P < 0.01$ and $***P < 0.001$.

	Ego or actor χ^2test	Type of actor Fisher test	Type of kinship Fisher test	Geographical location - χ^2test
Information network				
clove vs. vanilla	3.98e-13***	0.0351*	0.2027	0.0401*
banana vs. clove	0.9696	0.8529	0.7337	1
banana vs. vanilla	6.35e-13***	0.0028**	0.3462	0.0486*
Planting material network				
clove vs. Vanilla	1	0.0114*	0.0905	1.17e-05***
banana vs. clove	1.43e-07***	0.3606	0.1379	0.0012**
banana vs. vanilla	1.23e-05***	0.0513	0.8351	0.1648

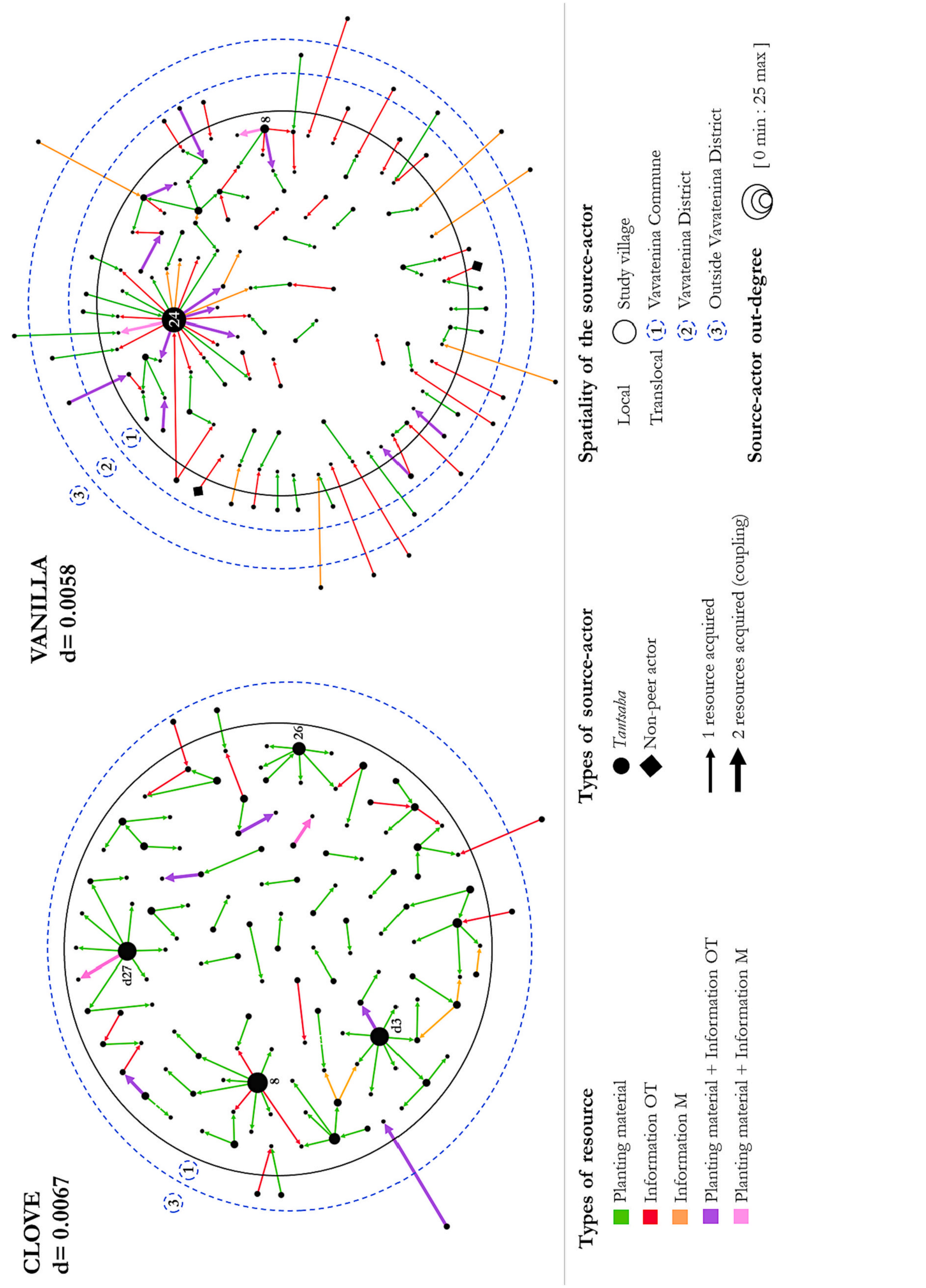

Fig. 3. The circulation networks based on information and planting material exchanges for clove (left panel) and vanilla (right panel). In the legend, "Information OT" refers to information sourced through oral transmission, and "Information M" through mimicry.

4.1.2. Comparison of the sources of planting material

The farmers reported only obtaining vanilla cuttings, while for clove they reported mainly obtaining seedlings (77%) and seeds (23%) (Fig. 2). The majority of planting material exchanged originated from cultivated plots: clove seeds and seedlings only came from *tsabo*, and vanilla cuttings also mainly came from *tsabo* (83%) but could also originate from other sources (1 nursery, 1 market, 8 chance roadside encounters).

Self-supply (source-ego) represented only a small proportion of clove and vanilla planting material declared by the farmers we interviewed (respectively 10% and 11%; p-value = 1; Fig. 2; Table 1). Significant differences in the proportions of the different types of source-actors were found between the clove and the vanilla circulation networks (p-value = 0.0114). The category labelled “relative” accounted for 88% of the source-actors in the clove network and for 74% in the vanilla network. The categories labelled “friend” and “villager” types represented low proportions, respectively 7% and 5% in the clove network, and 10% and 6% in the vanilla network. The latter was the only network containing a category of “unknown” source-actors of planting material (10%).

No significant link was found between the crop species and the types of kinship reported as sources of planting material (p-value = 0.0905), as the dominant kinships in both networks were the father and his kin (clove: 65%; vanilla: 49%), followed by the mother and her kin (clove: 26%; vanilla: 23%). However, the vanilla network had a higher proportion of source-actors corresponding to brother, sister or their kin (28% versus 8% in the clove network).

The χ^2 test attested to a significant link between the species and the geographical location of the source-actors (p-value = 1.17e-05). Three external source-actors of planting material (one in Vavatenina commune and two in Antsinanana region) were found in the clove network (Fig. 3, Fig. 4). The vanilla network had 13 external source-actors located in different villages that belong to the Vavatenina commune, 4 located in the Ambohibe commune, one in the Anjahambe commune, and one outside Vavatenina district (Fig. 3, Fig. 4).

4.1.3. Comparison of the circulation network of the two resources

The measured diversity of source-actors based on the category of source-actor and its geographical location and including the two resources, showed that the vanilla network had the highest richness and Shannon indices (Table 2), meaning it had more different categories of source-actors. The values of Pielou index (Table 2) show that the abundance of the different categories of source-actor was more equitable in the vanilla network than in the clove network, meaning that the clove network had fewer source-actors. The two circulation networks had a low density but the density of the clove network was higher (density = 0.0067) than that of the vanilla network (density = 0.0058). Concerning the number of couplings (i.e. when planting material and information come from the same source and circulate through the same tie), the clove network had fewer (N = 7/107 ties corresponding to 6.5%) than the vanilla network (N = 14/118 ties corresponding to 12%). In the vanilla network, one central source-actor (n°24, out-degree = 25) was

Table 2
Indices of diversity of planting material and information source-actor measured for clove, vanilla and banana from data provided by farmers on the nature of the relationship between the source-actors and their geographical location. The higher the Shannon index, the greater the diversity. Pielou equitability: the closer it is to 1, the more similar the abundances of each type of source.

	Clove	Vanilla	Banana
Richness	7	**14**	8
Shannon	0.914	**1.917**	1.306
Pielou equitability	0.469	0.726	0.628

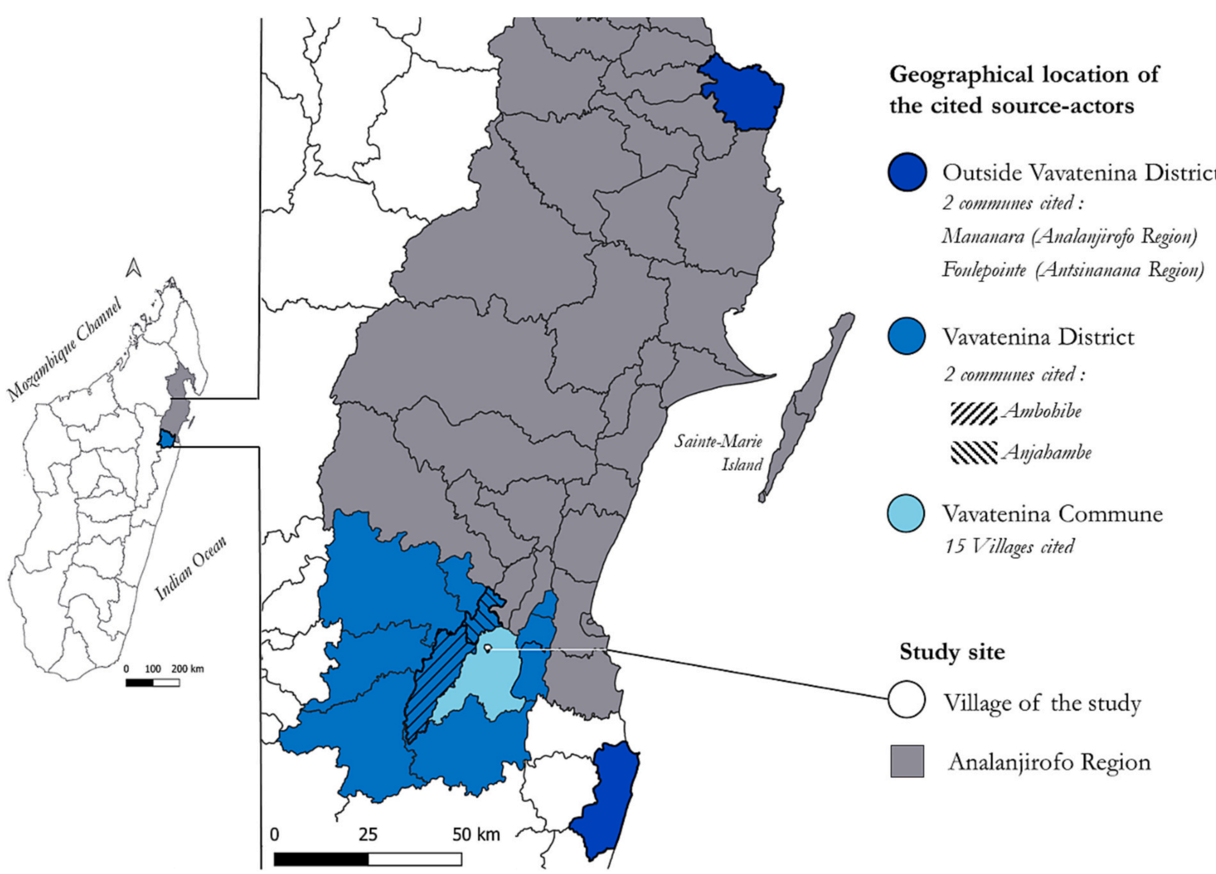

Fig. 4. Mapping of the geographical locations of the sources used by the farmers to obtain planting material and information related to three agroforestry species (clove, vanilla, banana).

identified, whereas the clove network centered around four source-actors with a lower out-degree value (n°d27 = 9, n°d3 = 9, n°8 = 9, n°26 = 5).

4.2. Comparison between banana and clove-vanilla

4.2.1. Comparison of sources of information

Information concerning banana was obtained through experimentation in 60% of the events studied (source-ego; Fig. 5) which differed significantly from how vanilla-related information was obtained (8%; *p*-value = 6.35e-13; Table 1) but not from the acquisition of clove-related information (61%; *p*-value = 0.9696). In the case of information coming from source-actors, oral transmission represented 65% and mimicry, 35%.

Differences in the proportions of the different categories of source-actor in the information networks were found between banana and vanilla (*p*-value = 0.0028) but not between banana and clove (p-value = 0.8529). Among the source-actors, the main category for banana was "relatives" (65%), followed by "villagers" (30%) and "friends" (5%) (Fig. 5).

No differences in the proportions of kinship ties were found between the farmers interviewed and the source-actors between banana and clove (*p*-value = 0.7337), nor between banana and vanilla (*p*-value = 0.3462). Whatever the gender of the farmer, information about banana mainly originated from the farmer's father or his kin (84%), the other kinships mentioned were the farmer's mother and her kin (8%), the husband (4%) and the brother, sister or their kin (4%).

A significant link was found between the cultivated species and the geographical location of the source-actors when banana was compared with vanilla (*p*-value = 0.0486) but not with clove. The banana information network only contained two external source-actors in Vavatenina commune, one in Ambohibe commune, one in Anjahambe commune and two outside Vavatenina district (Fig. 4, Fig. 6). This number of external sources in the banana information network ($N = 6$) was close to the number in the clove network ($N = 5$) and significantly lower than that of the vanilla network ($N = 29$).

4.2.2. Comparison of sources of planting material

The farmers reported only obtaining offshoots of banana most of which (87%) were collected in the *tsabo* and (12%) in *ambany trano*, plus two exchanges that took place during chance roadside encounters. The acquisitions documented concerned 14 landraces, three of which accounted for 65% (28% *voantsiroko*, 25% *betavia ambo* and 12% *betavia hiva*). Self-supply represented 42% of the total number of banana offshoot acquisitions reported by the farmers (source-ego; Fig. 5). This proportion differed significantly from the self-supply of planting material found for clove (10%; *p*-value = 1.43e-07) and vanilla (11%; *p*-value = 1.23e-05). The main category of source-actor was "relative" (80%) and to a lesser extent "friend" (12%), "villager" (7%), and one case of "unknown" (Fig. 5).

No significant link was found either between the species and the category of source-actor (banana vs. clove, *p*-value = 0.3606; banana vs. vanilla, *p*-value = 0.0513), or between the species and the category of kinship (banana vs clove, *p*-value = 0.1379; banana vs vanilla, *p*-value = 0.8351). The main kinship category was the father and his kin (52%), followed by the brothers, sisters and their kin (26%) and the mother and her kin (21%) (Fig. 5).

The χ^2 tests attested to a significant link between the species cultivated and the geographical location of the source-actors when banana and clove were compared (*p*-value = 0.0012) but not when banana was compared with vanilla (*p*-value = 0.1648). The circulation network of banana offshoots comprised 16 external source-actors from different villages of the Vavatenina commune, three from different communes of the Vavatenina district and two from the Antsinanana region (Fig. 4, Fig. 6). This number of external source-actors of banana planting material ($N = 21$) was closer to that calculated for vanilla ($N = 19$) than for clove ($N = 3$).

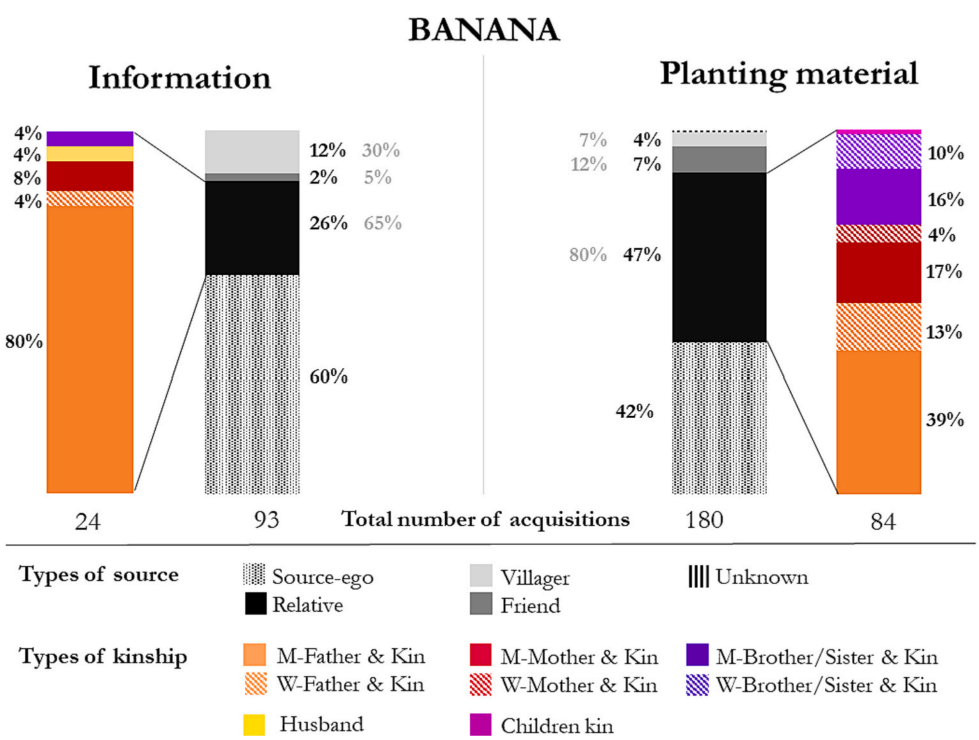

Fig. 5. Proportions of the different types of information sources (left panel) and sources of planting material (right panel) in the case of and planting material. Percentages in black were calculated relative to the total number of acquisitions, those in grey, relative to the total number of source-actors (i.e. the number of source-ego subtracted from the total number of acquisitions). The proportion of the kinship category "children kin" in the source of clove planting material was 1%.

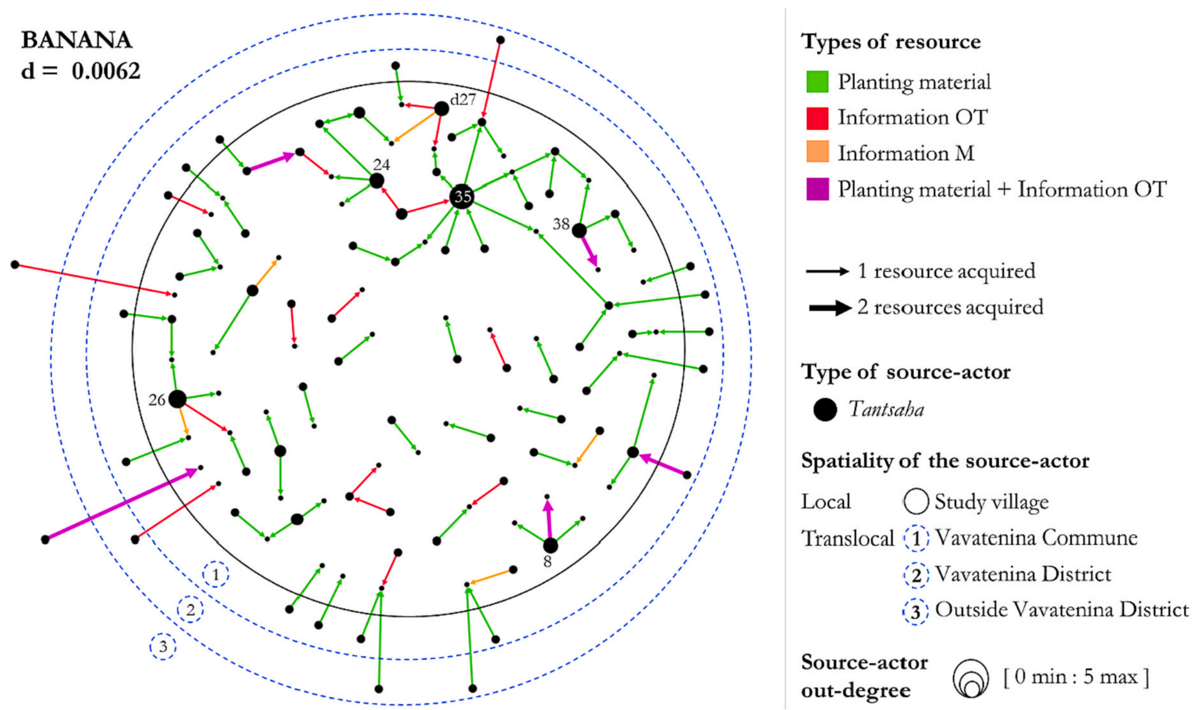

Fig. 6. The circulation network based on information and planting material exchanges for banana. In the legend, "Information OT" refers to information sourced through oral transmission, and "Information M" through mimicry. NB: The number of external sources visualized on the fig. ($N = 17$) is lower than the number reported by the surveys (N = 21) because in four cases, the surveyed farmer obtained the two banana landraces from the same external source-actor.

4.2.3. Comparison of the circulation networks of the two resources

The banana planting material and information network was characterized by a diversity of source-actors closer to these measured for clove than for vanilla (Table 2). However, the value of Pielou index indicated that the abundance of different categories of source-actor was more equitable in the banana network than in the clove network, meaning that it had fewer rare source-actors. Compared to clove and vanilla, the density of the banana network (d = 0.0062) was close to that calculated for clove, fewer couplings (5%, $N = 5/97$ ties) and, like the clove network, it was centered around several source-actors with an out-degree no greater than five (n°35 = 5, n°26, n°24 = 3, n°d27 = 3, n°8 = 3) (Fig. 6).

5. Discussion

5.1. Effect of the timing of the introduction of the crops, the farmers' status and the crop propagating systems on agrobiodiversity sourcing networks

Mobilizing diversified and external sources of agrobiodiversity to transform agroecosystems: the example of vanilla | Compared to the clove and banana networks, both planting material and information networks for vanilla were characterized by more diverse sources. Farmers were particularly connected to sources with which they had no previous relationship (i.e. unknown or non-peers) and external to their village. This supports our hypothesis concerning the effects of the timing of introduction and of the crop propagation system on how farmers obtain and propagate a crop. Vanilla has been present in the Vavatenina area for a relatively long time (Dandoy., 1973), but until the price boom in the early 2000s, its cultivation remained limited (Hänke et al., 2018; Mariel et al., 2022b). Consequently, the source of vanilla cuttings was limited in our study area and we can assume that initially no farmers in the village had a lot of knowledge concerning vanilla. The rise in the market price for vanilla increased farmers' motivation to plant more vanilla in their *tsabo*, encouraged them to find sources of cuttings and information from experts, mostly from outside the village. The low multiplication rate of this crop most likely accentuated this phenomenon.

The cultural geographical mobility of Malagasy farmers, in our case, to areas recognized for their vanilla plantations, seems to have played an important role in the introduction and expansion of vanilla in our study area (66% of surveyed farmers reported seasonal mobility or past long-term mobility). Mananara, Sambava and Antala are examples of areas where vanilla cultivation has had significant local economic impacts, enriching farmers and leading to the development of large-scale farms that employ seasonal workers. The attractiveness of these areas was already documented in 1959 ("*seasonal migrations for the duration of an agricultural season*" in a "*territory of large-scale cultivation [to] harvest vanilla in the Sambava-Antala area*" Defos du Rau, 1959). Moving to these areas creates opportunities to discover different farming practices whose associated knowledge and planting materials can then be brought back to the migrant's native village (Rockenbauch et al., 2019a).

We have shown that the vanilla network of information and cuttings shows is centered on a farmer who was designated an expert by the interviewees. The farmer concerned has been growing vanilla for a long time and has several hundred plants in his *tsabo*, but the results of his plantations only became visible to other farmers in the village following the boom in vanilla prices, as he invested the money he earned in improving his living conditions. Like other studies, our analysis shows how success and enrichment transform a farmer into an attractive source of agrobiodiversity and a "good example' to copy (Poudel et al., 2015; Rockenbauch et al., 2019a; Isaac et al., 2021).

Clove and banana networks: different patterns of local circulation driven by the timing of the introduction and their propagation system | Clove and banana have been grown by more farmers and for longer than vanilla in our study area. These factors may also explain the higher proportion of farmers who acquired information through experimentation, i.e. learning by doing in their own *tsabo*, and use banana offshoots from their own *tsabo* and clove from *tsabo* belonging to members of their family. The extent of experimentation may be linked to the fact that farmers are used to cultivating clove trees and banana, and are consequently confident in their adaptability to local conditions and in their performance (Blanc-Pamard and Ruf, 1992; Danthu et al., 2014), which is not the case for vanilla (Mariel et al., 2021). The local environment is a reliable source of information for developing and consolidating knowledge (Berkes and Berkes, 2009), and in our case study, also seems to apply to agrobiodiversity management. The importance of source-ego of banana offshoot and relatives in the supply of clove confirm our hypothesis that the high multiplication rate of these two species, combined with how long they have been cultivated in the area, have created a locally available pool of planting material which new generations can use as a source.

However, some of our results were unexpected: first, self-sourcing of clove planting material resembled that of vanilla (i.e. was lower than expected) and, second, a larger supply of planting material originated from external source-actors in the banana network than in the clove network. Concerning the low self-sourcing of clove seeds and seedlings, we hypothesize that farmers inherited *tsabo* with few or no clove trees, or with young clove trees that were not yet sufficiently mature to produce seeds. However, this result can reflect the values vehicled by the exchange of planting material that self-sourcing does not. Through exchange, farmers show they can rely on the source and on the quality of the planting material because they are investing in the future of their farm. Exchanging a material resource creates relationships between family members and others, and contributes to social cohesion based on mutual trust that plays a key role in times of scarcity (Badstue et al., 2007; van Niekerk and Wynberg, 2017). The high proportion of external sources of banana offshoots is rather surprising given the ease with which banana can be propagated, apart from the difficulty involved in transporting an offshoot. This result may be evidence for the farmers' wish to cultivate a diversity of landraces for the different uses they make of the fruit, leaves and stems (Mariel et al., 2022a; pers. obs) and for which the amount of planting material available within the village is limited. Thus, through kinship relationships with neighboring villages, the interviewees obtained landraces that they had not yet cultivated in their *tsabo*. This result is also in line with the idea of the importance of exchanges of crops in maintaining social ties, as frequently observed in rural communities (Haudricourt, 1964).

5.2. Socio-cultural processes revealed by comparing planting material and information networks

In this section, we change our point of view and discuss our results not by comparing the three species, but by comparing planting material and information. These two resources are essential to favor and support resilient agriculture based on agrobiodiversity (Altieri and Nicholls, 2017). If one of these is lacking, either the crop species or variety cannot be cultivated (lack of plant material), or it is not done properly (lack of knowledge), and in both cases, there is a high risk that the species or variety will not be maintained in the agroecosystem. The literature on farmers' seed and knowledge systems shows that local modalities of access to and exchange of these resources can be very different, which calls for attention to their specific features (Labeyrie et al., 2021a).

***Fihavanana*-based relationships: a cultural value altered by the monetarization of agriculture? |** Overall, the farmers we interviewed mainly obtained resources from their peers and rarely from other actors, such as NGOs, national development organizations, or agricultural extension services. This low proportion of sources other than peers and the predominance of kinship relationships are widely observed in rural societies elsewhere (Kiptot et al., 2006; Labeyrie et al., 2016; Calvet-Mir and Salpeteur, 2016). In our case study, we offer different explanations. First, development organizations were rarely cited as sources of plants and information because these organizations - whether national ones or NGOs - are barely active in our study area. Further, the way representatives of the administration interacted with the farmers during the colonial period (Dandoy., 1973), and the way the relationship evolved after independence (Aubert et al., 2003) probably limited the farmers' willingness to interact with these entities. Indeed, the coercive aspect of the actions undertaken by the administration, in particular the obligation to pay taxes and the ban on shifting cultivation (*tavy*), had left a strong impression on the farmers and did not foster a relationship built on trust between the decentralized state bodies in rural areas and the local population, thereby limiting the adoption of the techniques and equipment they proposed (Dandoy., 1973; Aubert et al., 2003).

Secondly, the importance of kinship relationships in the circulation of information and crops can be linked to the cultural and moral values embodied by *fihavanana*-based relationships: almost 90% of the interviewees said the people they trusted most were their blood relations and friends. The Malagasy people place the family at the heart of many concerns and decisions: above all, they rely on it in case of need (e.g. when a young household is first setting up, in the face of climatic or economic hazards), and consider it strongly in their farming strategies (Dandoy., 1973; Tilghman, 2019). For instance, one way of creating a legacy for future generations is maintaining and enriching agrobiodiversity through renewal and diversification. The high proportion of farmers who obtain information from their relatives was evidenced by farmers who told us: "*we must follow in our parents' tracks because we see the results of their practices in their tsabo*" (M.) and because "*our parents are the ones with the most experience*" (M.V). Our study is in agreement with the literature showing the relevant role of kinship in seed and knowledge exchange systems (Calvet-Mir and Salpeteur, 2016). However, the importance of *fihavanana* is the subject of debate given that other authors have underlined the impacts of cash crops on farmers' social relationships. For instance, Llopis et al. (2020) reported that the enrichment of farmers associated with vanilla cultivation has contributed to the '*monetarization of the community*', i.e. the replacement of donation by monetary exchange.

Effects of marriage rules and gendered activities on the types of kinship mobilized| Our results show that a farmer's father and the father's kin were the main kinships used by the interviewees to acquire planting material and information. But male farmers were more likely to obtain planting materiel from their siblings and from their mother or her family, than information. These observations highlight, on the one hand, the effects of gendered farming activities and, on the other hand, inheritance and marriage rules on the way farmers source planting material and information. In our case study, apart from harvesting and vanilla pollination, women are barely involved in *tsabo* management. On the contrary, starting in childhood, fathers take their sons with them to *tsabo* to pass on their knowledge and their crop species management practices. By tradition, male farmers are the main holders of knowledge about agroforestry species and consequently the main sources of information. As mentioned above, the gender effect was less pronounced in the circulation networks used for planting material. A relatively high proportion of interviewees obtained planting material from their mother or her family, regardless of whether the farmer being interviewed was a man or a woman. The significant role played by women in the supply of planting material may be linked to the local rules concerning land inheritance, which are the same for children of all genders. When a man and a woman marry, they share the land they have inherited to satisfy family needs, and the *tsabo* inherited by a woman is therefore a source of planting material. However, the patrilocal system, which requires the wife to move to the husband's village of origin, tends to reduce the role of women's *tsabo* in the supply of planting material, due to their distance from the family's place of residence. In this respect, our study is in line with others that underline the structuring role of local rules concerning social organization in the circulation of agrobiodiversity (Deletre et al., 2011; Labeyrie et al., 2016).

5.3. What are the implications of our results for resilience?

Our research provides empirical evidence that farmers' sourcing networks combine both weak more geographically distant bridging ties that foster innovation (case of vanilla networks), and strong local ties that facilitate local circulation and cohesion (cases of clove and banana networks). The combination of this characteristic network structure is cited in the literature as favoring resilience (Barnes et al., 2017).

Factors of a successful bottom-up innovation| Our study underlined the limited role that development organizations may have had in agroforestry dynamics, whereas a role for these organizations in the dissemination of new practices has been reported in other areas experiencing agroforestry dynamics (Isaac et al., 2007; Isaac, 2012; Cadger et al., 2016). Considering the development of agroforestry and, more recently, that of vanilla, as innovations, we are looking at an example of bottom-up innovation (Rockenbauch et al., 2019a). Several studies have demonstrated the role of density in the circulation of agrobiodiversity and hence in the adoption of innovation (Tittonell, 2020; Kabirigi et al., 2022). However, the networks analyzed in those studies were characterized by a very low density, i.e. a predominance of inter-individual exchanges and little circulation between the farmers within the village. First, we link this observation to the importance of the family unit in the share of material and immaterial resources but, second, to the high proportion of self-supply cross-referred with the high percentage of farmers (almost 20%) who said "*nobody*" in reply to the question of who they would go to if they needed agricultural advice. This answer reflects the individualism of farmers linked to the expansion of cash crops and their effect on insecurity in rural areas (Llopis et al., 2020; Osterhoudt, 2020). The enrichment of some farmers thanks to cash crops has fueled a feeling of envy, leading some people to steal vanilla crops, and in response, some farmers to kill the thieves. These robberies and murders, which mainly occur in the Mananara and Sava areas, have been widely reported in the media and have created a climate of fear and mistrust. Despite the low density of the network studies, our work enabled us to identify several factors that may have contributed to the development of vanilla thanks to a bottom-up innovation system.

First, farmers' mobility, for example for seasonal employment, migration or patrilocality, may play an important role in the introduction of new crops and practices (Rockenbauch et al., 2019a), in our case, vanilla and the tree that is used as a stake. This implies a process at individual scale that goes beyond some principles of *fihavanana* and, in particular, "*not to behave differently from others*" at the risk of being subject to community disapproval (Sandron, 2008). At community level, we identified four farmers as central sources of planting material and information. Their nodal place in the networks may be associated with personal attributes (e.g. their social status, level of knowledge) and success in farming, as already documented by other authors (Díaz-Reviriego et al., 2016; Thomas and Caillon, 2016). Moreover, the significant proportion of information acquired through mimicry that we observed, suggests that this is an important way for farmers to learn agricultural practices, and one that can facilitate the circulation and adoption of innovation. For instance, some interviewees explained that they chose the species they used to stake their vanilla plants because "*many farmers use this species in the village*". Thus, nodal farmers combined with mimicry are factors that may have contributed to the bottom up innovation we observed in our case study.

Local and informal networks based on strong ties to maintain and expand crop diversity | Whatever the type of species we studied, we observed that farmers' planting material and information sourcing networks mainly involved ties between farmers within their own village and connected through kinship. We therefore highlighted community based network that was identified as efficient networks to recover and restore crop diversity after a shock (Fenzi et al., 2022). In the literature, kinship relationships correspond to 'strong ties' built based on trust and solidarity, two important characteristics of social relationships for strengthening social capital and enhancing resilience (Qurniati et al., 2017; Galaso, 2018). Kinship relationships also support vertical transmission, known to play a central role in local adaptation in rural societies (Reyes-García et al., 2009). By reporting that peer farmers, *fihavanana*-based relationships and kinships are the primary source used to acquire planting material and information, our study underlines the issue of considering trust and vertical transmission to conserve crop diversity and strengthen agroforestry dynamics (Saint Ville et al., 2016; Qurniati et al., 2017).

Except the socio-cultural processes that tend to shape network structure and influence the circulation of innovation at community scale, the individual scale offers other perspectives that help understand the adoption of innovation. Thus, for a deeper understanding of the processes involved in agroforestry dynamics in the Vavatenina region, complementary data should be collected on farmers' strategies and motivations, and how they are affected by economic factors (Andriatsitohaina et al., 2020) or climate change (Labeyrie et al., 2021b; Ruggieri et al., 2021).

6. Conclusion

Our comparison of the networks of three species (clove, vanilla, banana) revealed that farmers mobilized more diverse and external sources of planting material and information in the case of a recently introduced crop (vanilla) than for crop that had long been cultivated in the area (clove and banana). Self-sourcing and kinship relationships characterized the networks through which farmers accessed the latter. Our analysis of the differences and similarities between the three networks also underlines how species propagation and socio-cultural and economic factors influence farmers' access to agrobiodiversity. In our study area, the farmers' ability to observe, experiment, to maintain, multiply and diversify their crops in order to transmit them appears to have played a crucial role in crop diversity dynamics and their maintenance. The fact that learning practices is largely based on experimentation and mimicry can contribute to their efficient adoption, which in turn, allows them to adapt to new contexts. Our results pave the way for more in-depth research into network dynamics to better understand the long-term future development of such agroecosystems. In this perspective, socio-cultural factors require more attention, as they strongly influence crop status and values within the community and consequently the way agrobiodiversity is sourced and exchanged.

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CRediT authorship contribution statement

Juliette Mariel: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Isabelle Sanchez:** Formal analysis, Methodology, Validation, Visualization. **Nicolas Verzelen:** Formal analysis, Methodology, Validation, Visualization. **François Massol:** Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Stéphanie M. Carrière:** Formal analysis, Methodology, Validation, Writing – original draft. **Vanesse Labeyrie:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following ffnancial interests/personal relationships which may be considered as potential competing interests: Mariel reports ffnancial support was provided by CIRAD Montpellier-Occitanie Research Centre.

Data availability

Data will be made available on request.

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