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Received: 21 December 2020 | Accepted: 20 May 2021

DOI: 10.1002/pan3.10238

RESEARCH ARTICLE

PEOPLE AND NATURE | BRITISH ECOLOGICAL SOCIETY

Exploring farmers' agrobiodiversity management practices and knowledge in clove agroforests of Madagascar

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Funding information
ANR, Grant/Award Number: ANR-10-LABX-001-01 Labex Agro; Agropolis Fondation, Grant/Award Number: ANR-16-IDEX-0006; Occitanie Region, Grant/Award Number: ALDOCT 000588; Maison des Sciences de l'Homme of Montpellier

Handling Editor: Tobias Plieninger

Abstract

1. Interactions between farmers and agrobiodiversity are key drivers of agroecosystems sustainability and of the resilience of such systems to perturbations, but research into the human/nature interactions have overlooked some important aspects of agrobiodiversity management. In particular, farmers' ecological knowledge of the spatial organisation of plant diversity remains an open question, although knowledge and practices have major implications for the efficient and sustainable use of natural resources.
2. Our study addresses this question by analysing how farmers spatially organise plant species in agroforests based on their knowledge of species interactions and interactions with the environment. The Analanjirofo region on the north-east coast of Madagascar provides an interesting context to explore this issue in clove-based agroforests, as these systems were developed by farmers as a sustainable alternative to the traditional system of shifting rice cultivation.
3. Using an emic approach, that is based on the farmers' perspective, and participatory mapping, we studied plant diversity and its spatial organisation in 17 clove-based agroforests and in 28 management sub-units defined by farmers in a village of Vavatenina district. The plant functions and farmers' knowledge of plant interactions with clove tree were recorded in semi-structured interviews, and the interactions were represented in a cognitive map.
4. Farmers manage more than 50 plant species associated with diverse functions. Analysis of participatory maps identified four main types of species association as a function of the age of the clove trees and the associated plant diversity, and different spatial organisation patterns as a function of the topography and the surrounding species. Analysis of farmers' knowledge provided valuable insights into spatial organisation practices, how farmers perceive the adaptation of plant

species to biophysical heterogeneity of the environment and whether they can be associated with other species.

5. Our findings and methods pave the way for further interdisciplinary research on farmers/nature interactions to support the development of agrobiodiversity-based systems taking into account farmer and scientific knowledge and practices, especially in the tropics where the expansion of cash crops in input-intensive and mono-cropping systems has driven major disruptions to smallholder agriculture.

KEYWORDS

adaptation, agroforestry, ecological interactions, emic approach, ethnobotany, farmers' strategies, participatory mapping, smallholder agriculture

1 | INTRODUCTION

Research on local ecological knowledge, defined as 'a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission' (Berkes, 1999), shows that local communities have a specific and holistic understanding of their environment which contributes to their capacity to manage natural resources sustainably in an adaptive way to cope with the contingencies of environment and its spatial and temporal heterogeneity (Berkes et al., 2000; Folke, 2004). Knowledge specific to plant species, their uses and their management practices have been widely investigated because they concern socio-cultural, economic and environmental issues, such as biodiversity conservation (Garibaldi & Turner, 2004; Rafidison, 2020), the adaptation of agriculture to climate change (Labeyrie et al., 2021) or the food security of rural communities (Quave & Pieroni, 2015). Multiscale studies have revealed the role of indigenous perceptions and beliefs in the way local communities control soil erosion and fertility, manage land use and forest regeneration in secondary fallows (Barrera-Bassols et al., 2006; Carrière, 2002). All these studies emphasise how studying local knowledge of plants species helps understand human/nature interactions, and why such knowledge play a critical role in the resilience of socio-ecological systems (Congretel & Pinton, 2020; Folke, 2004).

In agroecosystems, interactions between farmers and agrobiodiversity, that is, the living organisms which contribute to agroecosystem functioning (Altieri, 2002; Jackson et al., 2007; Vandermeer & Perfecto, 1995), are a key dimension of human/nature interactions. In particular, it is widely acknowledged that agroecosystems in which farmers maintain a high level of plant diversity are more resilient to environmental and socio-economic perturbations (Isbell et al., 2017; Jackson et al., 2010; Lin, 2011). The agroecology literature particularly emphasises the importance of farmers' knowledge on how to organise the different plant species in space depending on the different ways species adapt to biophysical conditions, and how to associate plant species to account for their positive and negative interactions (Altieri, 2002). However, these aspects of farmers/agrobiodiversity interactions are still poorly understood, although an improved understanding of farmers' knowledge of agrobiodiversity and their associated management practices is crucial if agricultural development initiatives are to match local realities and meet global change challenges (Altieri & Nicholls, 2017; Labeyrie et al., 2021).

Agroforestry systems are a particularly illustrative type of agrobiodiversity-based cropping system in the tropics and subtropics where local communities interact with the forest daily (Nair, 1991). Agroforestry is defined as a system 'where woody perennials (trees, shrubs, palms, bamboos etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence' (Zomer et al., 2014). Agroforestry is recognised as an agroecological practice which, under certain conditions, ensures more sustainable agricultural production in the tropics (Mercer, 2004; Schroth & McNeely, 2011). The positive effects of agroforestry on agricultural productivity (Pumariño et al., 2015), biodiversity (Bhagwat et al., 2008; Jose, 2012) and the ecosystem services such as practice provides (Jose, 2009) contribute to the well-being of rural populations (Reed et al., 2017), increase resilience to climate change (Mbow et al., 2014) and help restore degraded landscapes (Hillbrand et al., 2017). However, the literature on agroforestry systems rarely focusses on famers' knowledge of the ecological interactions that drive the spatial organisation of plant diversity, although this domain of local knowledge is pivotal for efficient use of biophysical resources.

A few studies have described the spatial organisation of plant species, mainly in home gardens (Abebe et al., 2013; Méndez et al., 2001) in relation to soil fertility (Junqueira, 2015) or to altitude (Sahoo & Rocky, 2015), but none of these studies take farmers' knowledge into consideration as a way to understand the observed practices. Inversely, some studies on farmers' knowledge concern the interactions between plant species in relation to light and shade (Graefe et al., 2017; Smith Dumont et al., 2019), interactions between plants and invertebrates that influence soil fertility (Pauli et al., 2012) or the other types of ecological interactions that affect a range of ecosystem services (Ango et al., 2014; Cerdán et al., 2012; Rigal et al., 2018), but none analyse how farmers' knowledge of these ecological interactions influences the way the farmers organise the different plant species in space. The lack of studies linking farmers'

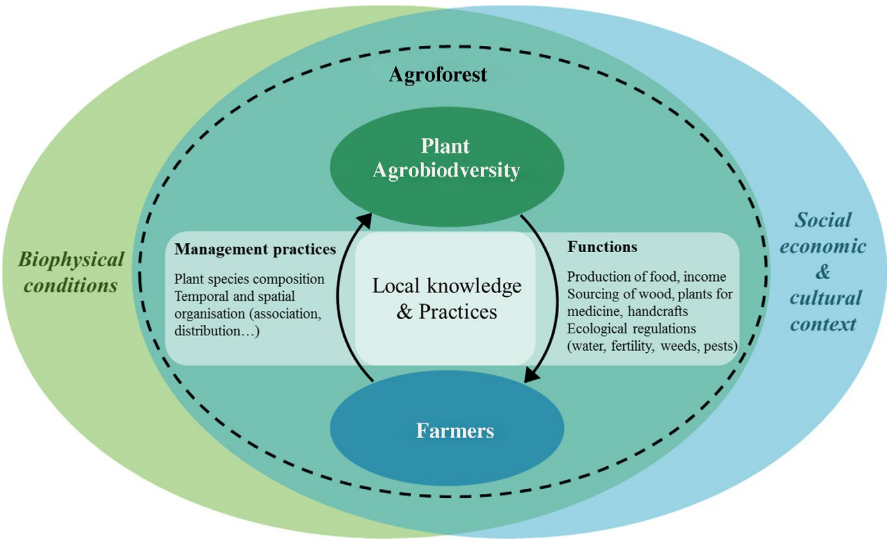


FIGURE 1 Farmers/agrobiodiversity interactions in agroforest at the interface of socio-ecological dynamics. Social, economic and biophysical drivers play at different scales: farm, local, national and global

knowledge of ecological interactions with the spatial organisation of plant species is mainly due to methodological challenges, as what is required is the articulation of methods that properly collect farmers' perceptions of their environment and analyse them from a local perspective, with methods that allow the quantification and measurement patterns of organisation of different plant species.

The aim of the present study was to fill this research gap by investigating how practices used to organise plant agrobiodiversity in space relate to farmers' knowledge of interactions between plant species and with their biophysical environment, based on a case study of clove-based agroforests on the north-east coast of Madagascar (Figure 1). An emic perspective, that is, how farmers perceive their environment and their own actions related to it (Olivier de Sardan, 1998), and different participatory methods and interviews were used to collect the data. First, the current diversity of plant species in agroforests and its functions were characterised along with the socio-cultural and economic drivers of this diversity. Second, the spatial organisation of plant species was analysed at two levels: species association within management sub-units and species distribution in the overall agroforest plot. Third, ecological knowledge of farmers was documented by focusing on the positive and negative interactions between plant species and clove trees, the key species in these agroforests. Finally, it was discussed how farmers' knowledge of ecological process shapes plant diversity and its spatial organisation, as a function of the biophysical heterogeneity of the environment and the other plant species.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was carried out in the Vavatenina district of the Analanjirofo region on the north-east coast of Madagascar (Figure 2). This region experienced massive planting of cash crops, especially coffee trees and spicy plant species, widely imposed by the colonial government at the beginning of the 20th century to satisfy the needs of the French metropolis and achieve the colony's financial autonomy through a flourishing export-based agriculture (Dandoy, 1973; Isnard, 1951; Ruf & Blanc-Pamard, 1992). Driven by economic factors, Analanjirofo region (literally 'Forest of clove trees') gradually became the main zone for plantations of clove trees *Syzygium aromaticum* instead of the emblematic shifting rice cultivation called *tavy* (Dandoy, 1973; Danthu et al., 2014). The two products provided by the clove tree, cloves and essential oil have become major sources of income, and currently, many Malagasy people from the east coast base their food security strategy on both rice self-production and income from clove and other cash crops (Droy et al., 2017).

The surveys were conducted in the village of Vohibary located 50 km from the coast and 5 km from the town of Vavatenina, the district's administrative centre. The village was chosen because an in-depth agrarian diagnosis conducted in 1966 enabled a diachronic approach (Dandoy, 1973). Most of the population belongs to the Betsimisaraka ethnic group. Between 1966 and 2019, the population of the village increased from 186 inhabitants (fewer than 50 households) to over 120 households, leading to the creation of a second hamlet on a hillside next to the original hamlet (Dandoy, 1973 and survey data from 2016).

The climate of Analanjirofo is humid tropical with 3,600 mm of rainfall per year and an average annual temperature of 24°C (Jury, 2003). Local people differentiate three seasons: a cool wet winter season from June to August, a hot summer season the rest of the year and a very wet period from December to March during which cyclones can occur. This coastal region is severely and regularly affected by cyclones, of which the last major ones were Honorinina (1986) Bonita (1996) and Ivan (2008).

The landscape is shaped by *tanety* (hills) rarely exceeding 400 m in height with slopes severely gullied by rainfall. The hydrographical network is structured around the main river, the Sahameloka, which is fed by numerous streams flowing from *tanety* springs and irrigates the rice-growing lowlands. Soil characteristics are closely correlated with topography. Soils of the lowlands are hydromorphic and accumulate organic and inorganic sediments. The *tanety* are occupied

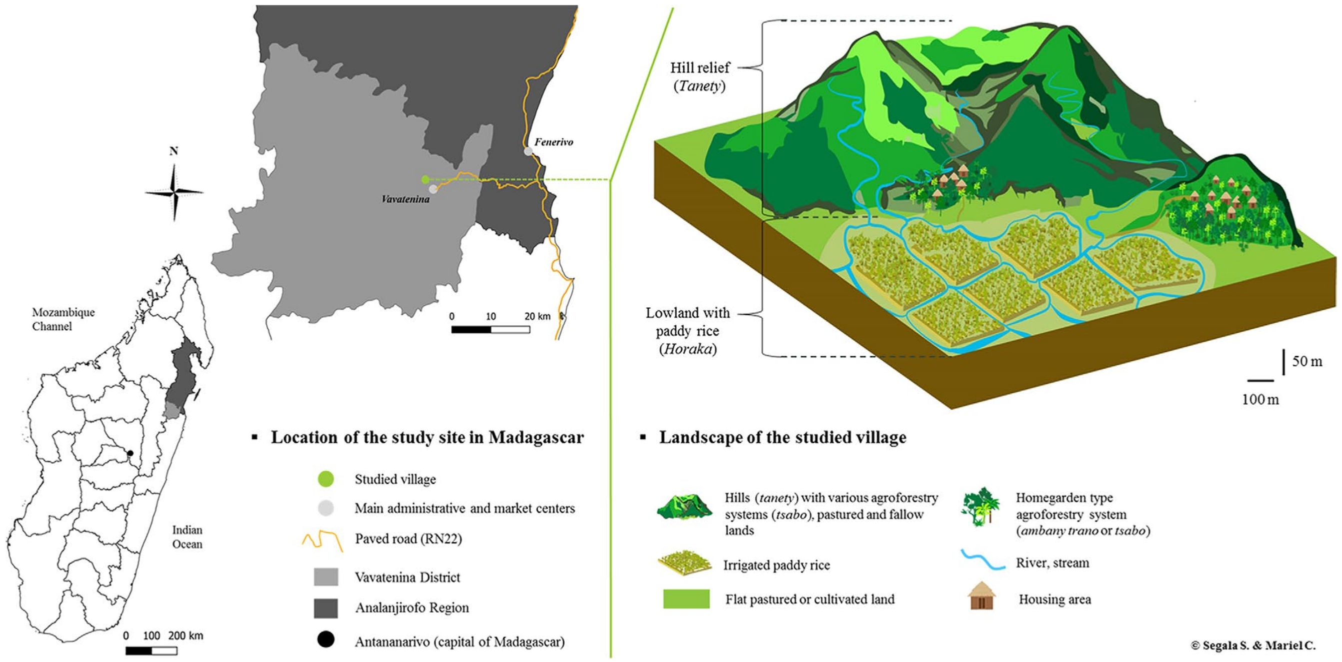


FIGURE 2 Location of the study village in Madagascar and its agrarian landscape

by eroded ferralitic soils with an overlying humus-bearing horizon (Dandoy, 1973). Along the topological gradient, the soil's texture, organic matter content and depth are variable and create heterogeneous environmental conditions for agriculture (Dandoy, 1973; author's own measurements made with an auger).

The humid tropical climate enables the cultivation of many different perennial and annual crops. The farmers cultivate paddy rice in the valley lowlands and irrigable flat lands. On *tanety*, they cultivate many types of crops in association, within a system they called *tsabo*, including trees (clove, coffee, fruit trees, various palms and others), lianas (vanilla and pepper) and herbaceous plants (sugarcane, cassava, maize, sweet potato and others). The crops are mixed in several different ways, in space and time, with variable densities and levels of stratification. The main characteristics described by farmers for a cultivated land to be a *tsabo* are: the presence of trees, the presence of at least two different crop species and the presence of food species. The crop species are also associated with some naturally occurring plant species, that is, non-cultivated species, including herbaceous and shrubby species, bamboo and palms that typically compose the local fallow vegetation (Rafidison et al., 2020). These *tsabo* correspond to the definition of agroforests given by Torquebiau (2000), that is, agro-silvicultural productive systems that combine commercial and subsistence products. One of the few in-depth studies of Analanjirofo agroforests concerns clove-based agroforests, that is, clove-based *tsabo* (Arimalala et al., 2019).

2.2 | Ethical approval

CIRAD ethics committee does not deliver ethical approval for research involving humans. To carry out the study, the Code of Ethics of the ISE (International Society of Ethnobiology) was followed. The work was conducted in collaboration with the University of Antananarivo in the frame of the 'Forêt et Biodiversité à Madagascar' collaboration platform (CIRAD-FOFIFA-University). A research permit was issued by the Secretary General of the 'Direction Générale de l'Environnement et des Forêts' before the study was undertaken. Before holding interviews in the village, a meeting was organised with the leader of the village and with the inhabitants to fully inform them of the purpose of the research and how it would be conducted. The methodology and the type of data collected were explained to farmers so they knew what participating in the surveys would involve. The future use of the data and the expected benefits of the study were described and discussed with the inhabitants. Written consent was provided by the village leader. The farmers participated voluntarily and were free from coercion, 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 region, helped ensure that local rules and customs were respected as well as the rights and well-being of the farmers interviewed.

2.3 | Data collection and analyses

2.3.1 | Sampling methods

The semi-directive surveys on farmers' practices and knowledge were conducted in 2019, in a sample of 17 voluntary Betsimisaraka farmers corresponding to the household head (14% of households of the village, with 1 woman and 16 men). The gender disparity was linked to the division of tasks between genders, men being responsible for planting trees in the *tsabo* in most cases. One *tsabo* per household was chosen based on the following criteria: the presence of clove trees to study only clove-based *tsabo*, the year the farmer began to work on its *tsabo* to cover different *tsabo* age categories and the location in the landscape so that the sample of *tsabo* was distributed over the geographical area of the village.

2.3.2 | Description of the agrobiodiversity from an emic perspective

To study the plant diversity of clove-based *tsabo*, the farmer being interviewed was asked to list on-site all the plant species present, using their common names. This list revealed which species the farmers considered to be important for them, in relation to their functions. It included planted species and spontaneously occurring species that are tolerated, or even encouraged by the farmers. The correspondence of common names with Latin names was established with the Betsimisaraka interpreter and Malagasy specialists from the University of Antananarivo. To document the functions of each species cited, two focus groups were organised: one in each village hamlet, and each included around 10 villagers, comprised two-thirds men and one-third women of different age groups.

2.3.3 | Analysis of practices of agrobiodiversity spatial organisation

The spatial organisation of plant species in clove-based *tsabo* was investigated using a participatory method to draw a map of each *tsabo* visited, based on the method of Méndez et al. (2001). These maps were used to describe two levels of spatial organisation of the species mentioned by the farmers: their overall patterns of organisation within *tsabo* (i.e. distribution and location according to the slope) and their association in sub-unit defined by the farmers, called micro-zone (Figure 3). The definition of micro-zone by Méndez et al. (2001) was adapted to the local context and to farmers' perceptions, and was defined as spatial sub-units within *tsabo* characterised by a given assemblage of plants that differs from that of the rest of the *tsabo* according to the farmers. Hence, micro-zones are units of homogeneous plant agrobiodiversity management defined from the farmers' perspective. The farmers were asked whether there was a pattern in the way they associated and managed plant species in their clove-based *tsabo*. If so, they were asked to outline the micro-zones on the map of their *tsabo*. Some farmers considered that plant species management was homogeneous throughout their *tsabo*, in which case the *tsabo* corresponded to one micro-zone. In this way, 17 participatory maps and a total of 28 micro-zones (with one to three micro-zones per *tsabo*) were obtained. The surface area of each clove-based *tsabo* and its micro-zones were measured by GPS. The average size of *tsabo* was

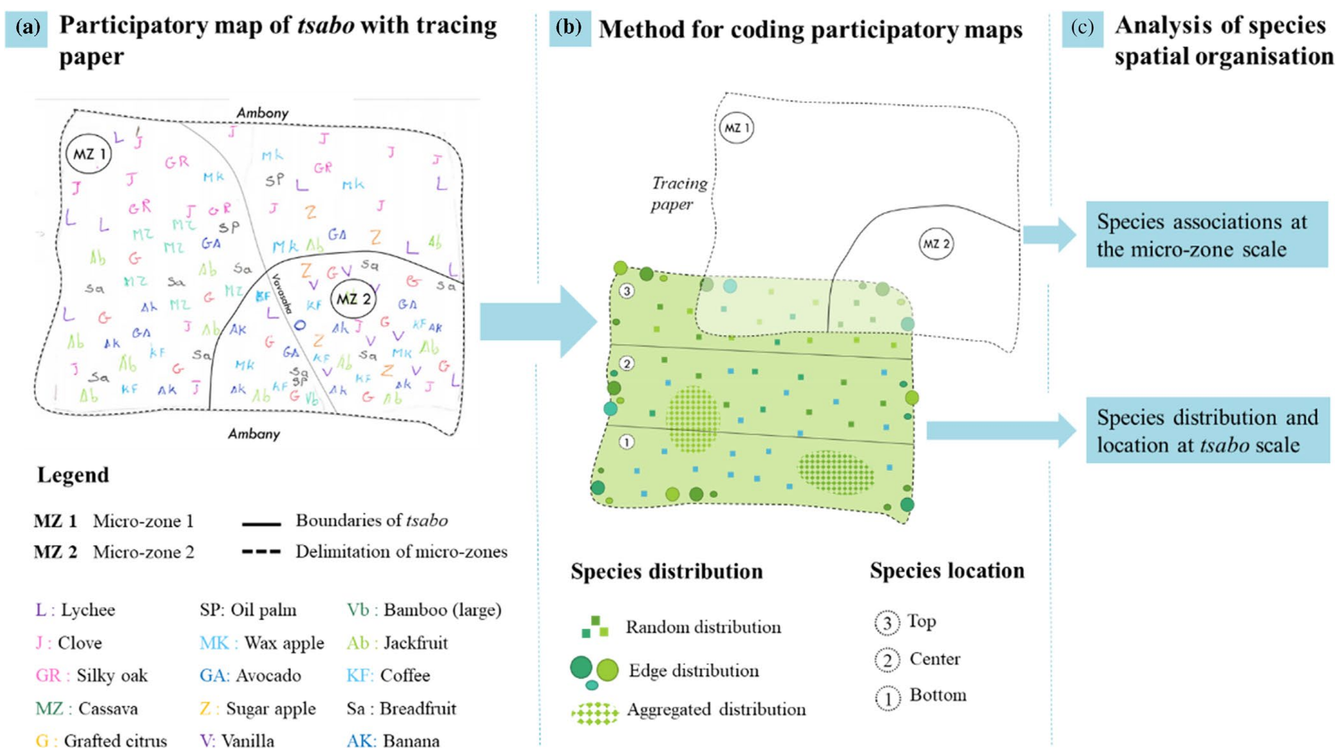


FIGURE 3 Methodology of data collection and analysis for the study of the two level of agrobiodiversity spatial organization within clove-based *tsabo*: the overall patterns of organisation (distribution and location according to the slope) and the associations of species in micro-zone. (a) Is an example of participatory map obtained (*ambony* is the upper part of the *tsabo*, *ambany* is the lower part and *vavazaha* corresponds to a stream or a runoff ravine). (b) Illustrates how the map with plant species indicated and the tracing paper were coded. (c) Gives the objectives of the analysis

0.5 ± 0.3 ha (min = 0.10 ha/max = 0.96 ha) and the sample of micro-zones was characterised by an average surface of 0.29 ± 0.23 ha (min = 0.03 ha/max = 0.87 ha) and an average slope of 17.7 ± 8.9° (min = 9°/max = 29°). Farmers' estimations of the abundance of vanilla and four frequent fruit trees (avocado, breadfruit, jackfruit and lychee) were recorded as the number of plants per micro-zone and, for clove trees, as well per age category. Indeed, exploratory surveys, conducted with the village chief and the elders, revealed that the age at which clove tree started producing cloves was a structuring factor for managing associated species because it does not have the same need for shade and light before and after becoming productive. According to the farmers, this is usually 10 years old, but may be younger or older depending on the growing conditions.

The participatory maps were coded to enable comparison of the spatial organisation of each species within *tsabo*. Two variables were selected to describe it: the position of the species according to the topographical gradient of the *tsabo* (i.e. top, centre and bottom; Figure 3) and the way in which each species was spatially distributed compared to the other species over the total area of *tsabo* (i.e. random, edge or aggregated; Figure 3). For each variable, the number of times a species was associated with it was counted. A Fisher's exact test was applied to the occurrence data of each variable to test whether each species was significantly associated to a given pattern of spatial organisation.

To characterise the practices of species association with clove trees, a typology of micro-zones was established based on the presence/absence of the different plant species and the age of the clove trees. Thus, before conducting the analysis, the micro-zones were separated into two groups according to the presence/absence of productive clove trees. In each group, the differentiation of the micro-zones was based on their similarity calculated with the Jaccard index: for each pair of micro-zones, the index corresponds to the ratio between the number of times a species is present in the two micro-zones and the total number of species excluding those absent from the pair (Abebe et al.,l., 2013; Borcard et al., 2011). This analysis was carried out in R (version 3.6.2) using the VEGDIST function of the VEGAN package (version 2.5.6). According to their similarity, the micro-zones were grouped in clusters defined through a representation based on the agglomerative complete linkage principle (Borcard et al., 2011). The different types of micro-zone were identified according to the first level of discrimination of the cluster. Each type of micro-zone was described by computing the mean plant species diversity and standard deviation, the species present in at least 60% of the micro-zones belonging to this type, and the mean densities of the six most frequent species associated with clove trees.

2.3.4 | Study of farmers' local knowledge on ecological interactions between agrobiodiversity and clove tree

Semi-structured interviews of about one hours were conducted with each farmer in the sample to document their knowledge associated with their practices resulting from the spatial organisation of plant species. The questions first centred on the plant species that had positive and negative interactions with the clove tree. The farmer was asked to explain each type of interaction described, particularly the ecological process that made an interaction positive or negative. A discussion of the participatory map enabled to understand the spatial distribution of all plants represented, and to deepen the structuring role of other frequent species.

The information gathered through the 17 semi-structured interviews was summarised and transcribed in the form of an interactions map. This work is based on the mental model framework used to represent the mental construction of actors and their perception of their environment and general phenomena (Özesmi & Özesmi, 2004). In our case, the map was intended to bring out farmers' perceptions of the ecological processes that occur in interactions between the clove tree and other species in *tsabo*. The map was built to represent the nature of the ecological process involved in the interaction (competition and growth, soil fertilisation, uptake of water from the soil, application of water to the plant or to the soil, etc.) and the physical element involved (soil, water and light). The resulting map revealed the total number of interactions described by the farmers (i.e. the association of one species with an ecological process) and the number of farmers (out of the 17) who mentioned that interaction.

3 | RESULTS

3.1 | Emic description of *tsabo* plant agrobiodiversity

The plant diversity cited by the farmers over the 17 clove-based *tsabo* sampled consisted of 51 species, including 36 trees, seven herbaceous plants, two bamboos, four palms and two lianas (Appendix 1). Plant species were grouped in 28 families, the most common being Myrtaceae represented by five species, followed by Fabaceae, Moraceae and Rutaceae, each represented by four species. The plant diversity measured and based on farmers' reports varied between the 17 *tsabo* in the sample. On average, the farmers listed 15 species (±4; range 8–22). Only 22% of the 51 species cited were present in at least half of the *tsabo*. The most frequent fruit species were jackfruit *Artocarpus heterophyllus* and lychee *Litchi chinensis*, followed by breadfruit *Artocarpus altilis* and banana (*Musa* sp.). Coffee *Coffea canephora* and vanilla *Vanilla planifolia* were the two cash crops also present in about half of the 17 clove-based *tsabo* studied. A total of 54% of the species were cited by fewer than eight farmers, and among these, 28% were cited by only one farmer each.

The villagers grouped plant species into nine function categories (Appendix 2). The *azahoam bola* category (literally 'gives money') corresponded to cash crops. The *bômafana* category (literally: 'what is heated up the day before and eaten the next morning') grouped species whose carbohydrate-rich fruits and tubers are consumed for breakfast or in the afternoon (breadfruit; yam, *Dioscorea* spp.; cassava, *Manihot esculenta*). The *dessert* category contained a wide range of fruit species consumed as snacks during the day and not considered to be nutritional foods by the farmers (*dessert voankazo* for fruit trees and *dessert* for non-woody species). Two species were used to make vegetable oil (*menaka*): oil palm *Elaeis guineensis* for cooking and coconut palm *Cocos nucifera* for haircare. The *rô-mazava* category (literally 'clear broth') corresponded to plants used to prepare broths to accompany rice. Two categories were defined for species that supply wood: *kitay* for firewood species (distilling and cooking) and *kakazo trano* (literally 'house tree') for woody species used for carpentry (poles, beams, fencing, roofs and boards) but sometimes also used as firewood. Some farmers assigned lychee and coffee to different uses, as *dessert voankazo* or *azahoam bola*. Lastly, some species had a use that did not correspond to a named category. This was the case for shade trees (*Albizia stipulata*, *A. lebbeck*), vanilla support trees (*Pachira aquatica*, *Ficus* sp., *Gliricidia sepium*) and *Raphia farinifera*, whose leaves were used to make string and woven stool seats.

3.2 | Practices of plant agrobiodiversity spatial organisation in *tsabo*

The results of the Fisher's exact test indicated significant dependence between the plant species and the two variables describing the spatial organisation: the location of species according to the topography of the *tsabo* (p value < 0.05) and the spatial distribution of species within (p value < 0.0005). Analysis of the spatial distribution variable (aggregated, edge and random) showed that the farmers tended to distribute the species randomly across the *tsabo*, particularly clove and silky oak, which were planted in the entire *tsabo* (Figure 4a). Only a few species, such as large bamboo and lychee, were usually planted on the border of *tsabo*. Aggregated distribution appeared to apply in particular to vanilla, banana, breadfruit and coffee (38% ≤ occurrence ≤ 60%). Concerning the spatial location variable, the farmers tended to prefer planting vanilla and coffee at the bottom of the *tsabo*, and to conserve large bamboo ('*be*' species) at the same location: more than 50% of individuals of each of these species were growing at the bottom of the *tsabo* (Figure 4b). The species that appeared to be the least demanding in terms of location were clove, lychee and *Gliricidia sepium*, as they were planted equally frequently in all three positions. The farmers seemed to let silky oak *Grevillea banksii* and traveller's palm *Ravenala madagascariensis* grow at the top of the *tsabo* (occurrence ≥ 50%): since, when these plants appeared spontaneously in other locations, the farmers removed them.

3.3 | Species association patterns within *tsabo*

The presence or absence of clove trees more than 10 years old (i.e. that produced cloves) differentiated two groups of micro-zones.

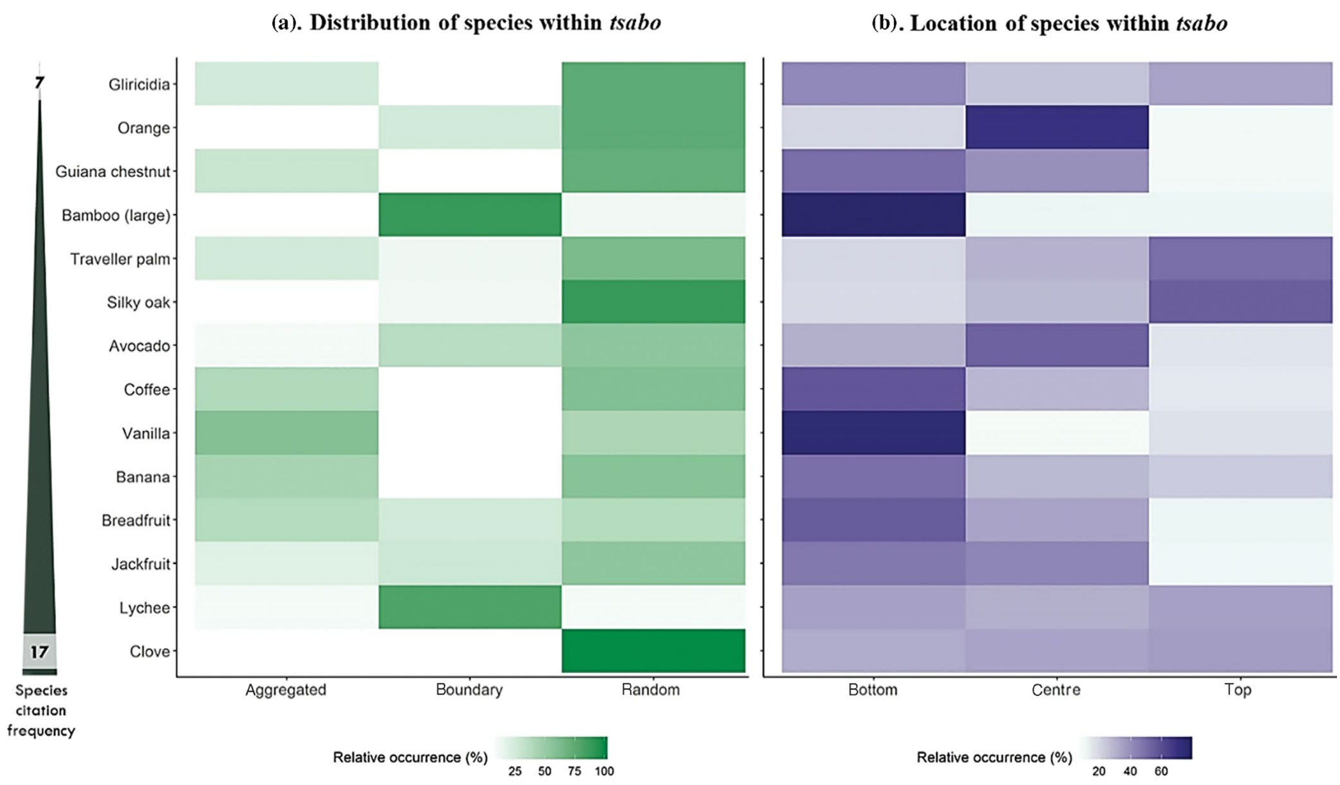


FIGURE 4 Heatmaps based on the relative occurrence of the 14 most frequent species in *tsabo* (frequency > 7, N = 17) according to the two variables selected for coding the spatial organization of species from the participatory maps, namely: (a) the way in which each species was spatially distributed compared to the other species and over the total area of the *tsabo* and (b) the position of the species according to the topographical gradient of the *tsabo*

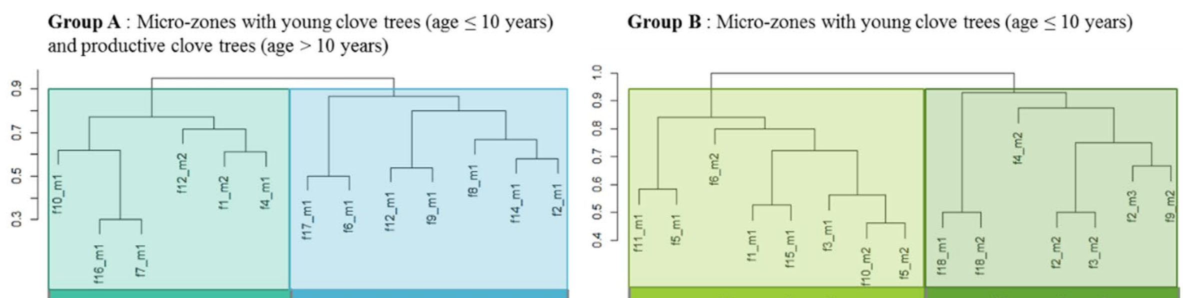
Group A (*tsabo* with mixed age clove trees) comprised 13 micro-zones with clove trees that were over 10 years old and in which 82% of the previously cited species occurred. Group B (*tsabo* with only young clove trees) included 15 micro-zones with no productive clove trees and in which 74% of the previously cited species occurred. In each group, the discrimination of the micro-zones at the first clustering level of the dendrograms led to the identification of two types of micro-zone per group: mixed age clove 1 and 2 (Ma1, Ma2), young clove 1 and 2 (Y1, Y2) (Figure 5).

In the type mixed age clove 1 (Ma1), 60% of the species cited by the farmers were represented. These six micro-zones contained high species diversity (mean: 13 ± 2, Figure 5). They were characterised by association of mature clove trees, young clove trees and various fruit species. The most frequent fruit species were banana, jackfruit, lychee, breadfruit, avocado and coffee, which were present in at least four out of the six micro-zones. The density of young clove trees was high (161 ± 177 trees/ha, Figure 6) compared to that of the mature clove trees (84 ± 65 trees/ha). This type was also characterised by a high density of lychee (17 ± 18 trees/ha) and included three micro-zones rich in vanilla with the highest and most variable density (132 ± 183 plants/ha), compared to the other types (Ma2 = 56 ± 139, Y1 = 108 ± 215, Y2 = 4 ± 12 plants/ha). The type mixed age clove 2 was less diversified than Ma1. It accounted for 54% of the previously cited species and the seven micro-zones it included had a mean species richness of 10 ± 3, with only mature clove trees present throughout this type of micro-zone (frequency = 100%). The other three species present in at least 60% of the micro-zones were traveller's palm, jackfruit and lychee. Unlike Ma1, type Ma2 was characterised by a high density of clove trees over 10 years old (194 ± 93 trees/ha) and a low density of clove trees under 10 years old (39 ± 50 trees/ha).

The two young clove types corresponded to the micro-zones with no clove trees over 10 years old. They were clearly distinguishable by their species composition: type Y1 micro-zones included 72% of all previously cited species, whereas those ascribed to type Y2 only included 38%. Type Y1 had high species richness (mean 12 ± 3 species) and stood out due to the presence of several fruit species: banana, lychee and coffee (present in seven micro-zones), along with jackfruit, breadfruit and avocado (present in six micro-zones). However, species composition was highly variable among type Y1, with few species shared between them. The densities calculated for young clove trees (230 ± 199 trees/ha, Figure 6), lychee (18 ± 24 trees/ha) and avocado (29 ± 42 trees/ha) were higher than in the other three types but also much more variable, as shown by the standard deviations. Half the micro-zones contained vanilla, whose density sometimes reached 632 plants/ha. Type Y1 therefore also displayed high variability in terms of structure linked to variations in the density of the species present. Unlike type Y1, the seven type Y2 micro-zones clearly had a lower mean species richness, with 5 ± 2 species, and only had clove trees under 10 years old in common. This type was therefore less diversified but had the highest density of young clove trees (268 ± 211 trees/ha). The other main species in this type was jackfruit, which occurred at high density (58 ± 108 trees/ha).

3.4 | Farmers' knowledge of ecological interactions

The farmers described a total of 31 interactions involving clove and another plant species (Figure 7): 21 with positive effects and 10 with negative effects. They referred to a total of 19 species among which eucalyptus was cited in different negative interactions by six farmers. The farmers explained that this was because eucalyptus roots affected soil water, soil fertility and plant growth. Lychee was also cited as a negative species for clove tree mainly because its canopy provided too much shade. According to the farmers, silky oak,



Micro-zones' type	Mixed age clove 1	Mixed age clove 2	Young clove 1	Young clove 2
Number of micro-zones (N = 28)	6	7	8	7
Diversity of the type (N = 51 species)	30 species	27 species	36 species	19 species
Average diversity of micro-zone type	13 ± 2 species	10 ± 3 species	12 ± 3 species	5 ± 2 species
Other species with a frequency ≥ 80%	Banana Jackfruit	Traveller's palm Jackfruit	Banana Lychee Coffee	-

FIGURE 5 Typology of micro-zones and its characteristics related to the agrobiodiversity present in micro-zones. The presence or absence of clove trees that are over 10 years old (producing cloves) discriminates two groups of micro-zones: group A and group B. Calculation of the Jaccard index for each pair of micro-zones and the representation in dendograms, based on the agglomerative complete linkage principle, differentiate four types of micro-zones: A1, A2, B1 and B2

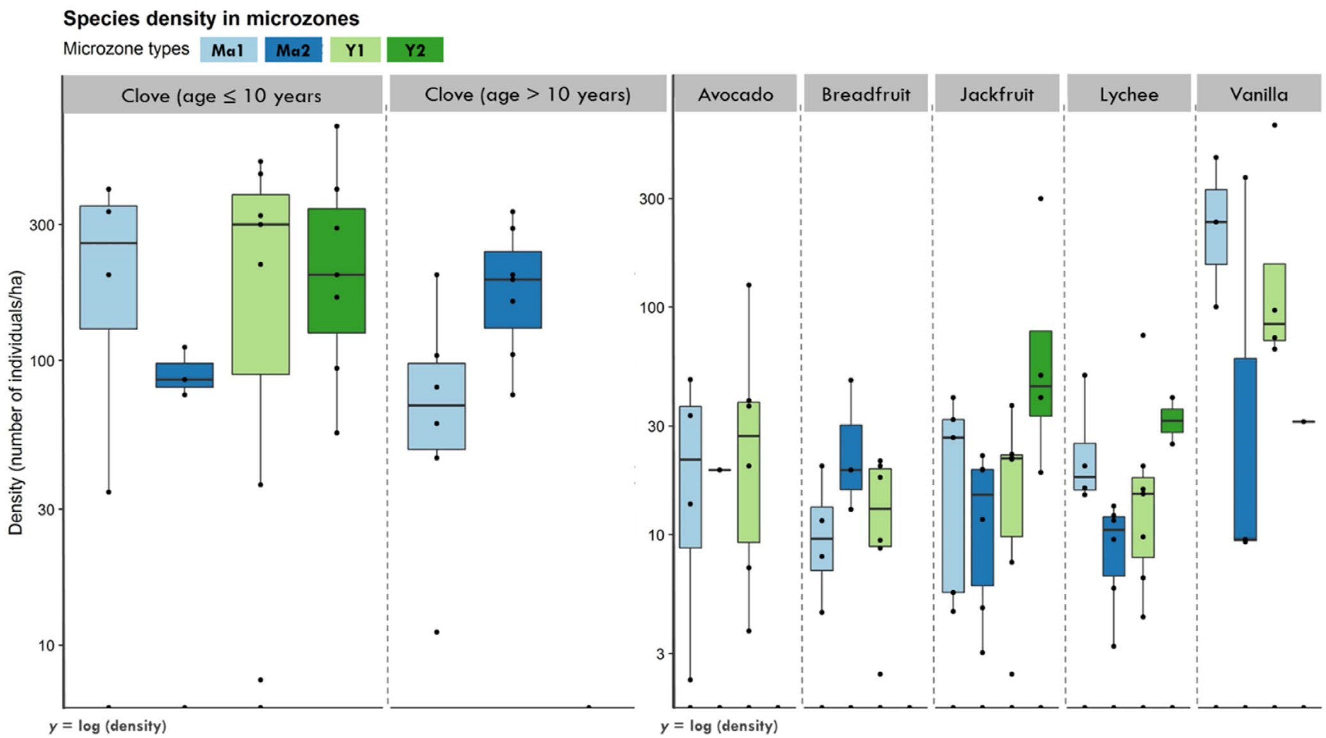


FIGURE 6 Average density for each micro-zone's type of productive and young clove tree, vanilla and four fruit tree species frequently occur in *tsabo* (avocado, breadfruit, jackfruit and lychee). The density was calculated from the number of individuals per species reported by the farmers and the area of micro-zones measured by GPS. The y-axis is log-transformed

cited by 11, interacted positively with clove trees in several ways, by improving the soil and its fertility, and by providing productive clove trees with water and adequate shade. The interaction map underlined the central place of the soil in the ecological processes described by the farmers: it was cited in 17 positive interactions and five negative ones. The clove tree's need for light also seemed to be an important factor, as 11 farmers pointed to the role of seven species in providing suitable shade.

During the interviews, the farmers described some other types of interactions, without specifying either the associated species or the ecological process involved. For instance, some farmers explained that all the species that were not taller than clove trees had positive effects on it (banana, coffee, silky oak, avocado and jackfruit). Conversely, all tall trees were considered to have negative effects on productive clove trees, as they cast too much shade on them.

4 | DISCUSSION

Our study of clove-based *tsabo* in the Vavatenina area in Madagascar confirmed that clove trees are associated with a range of perennial and herbaceous plant species, and in agroforests that present a higher level of plant diversity than the level measured in agroforests in nearby areas (Arimalala et al., 2019). However, comparison of the two studies was limited by differences in the methods used (lists vs. floristic species inventory). Our findings are in agreement with those of other studies showing that plant diversity in agroforests is linked to several functions (food, income, timber, stake, fertility, shade tree), and is chosen by farmers based on the contributions of plants species to agroecosystem functioning (e.g. shade, fertility, stake) and to fulfil household needs (Díaz et al., 2018; Reed et al., 2017). The discussion hereafter provides insights into how farm strategies influence the plant diversity that farmers cultivated and managed in their *tsabo* by taking socio-economic and environmental factors (e.g. cyclone, fluctuating sales price) into account. Our analysis of plant management practices revealed the existence of species associations and spatial organisation practices shared by most farmers. These practices can be partially explained by farmers' ecological knowledge, in line with other studies showing the close links between farmers' knowledge, their perception of the environment and their farming practices (Cerdán et al., 2012; Vuillot et al., 2016).

4.1 | Plant agrobiodiversity in *tsabo* is driven by the functions of the species as perceived by Betsimisaraka people and by farm strategies

This section describes and discusses the drivers of the current plant agrobiodiversity associated with clove tree in *tsabo*. First, plant diversity appears to be largely driven by the diversity of functions associated with the different plant species, allowing farmers to fulfil a range of needs, for instance, food production for human or animal

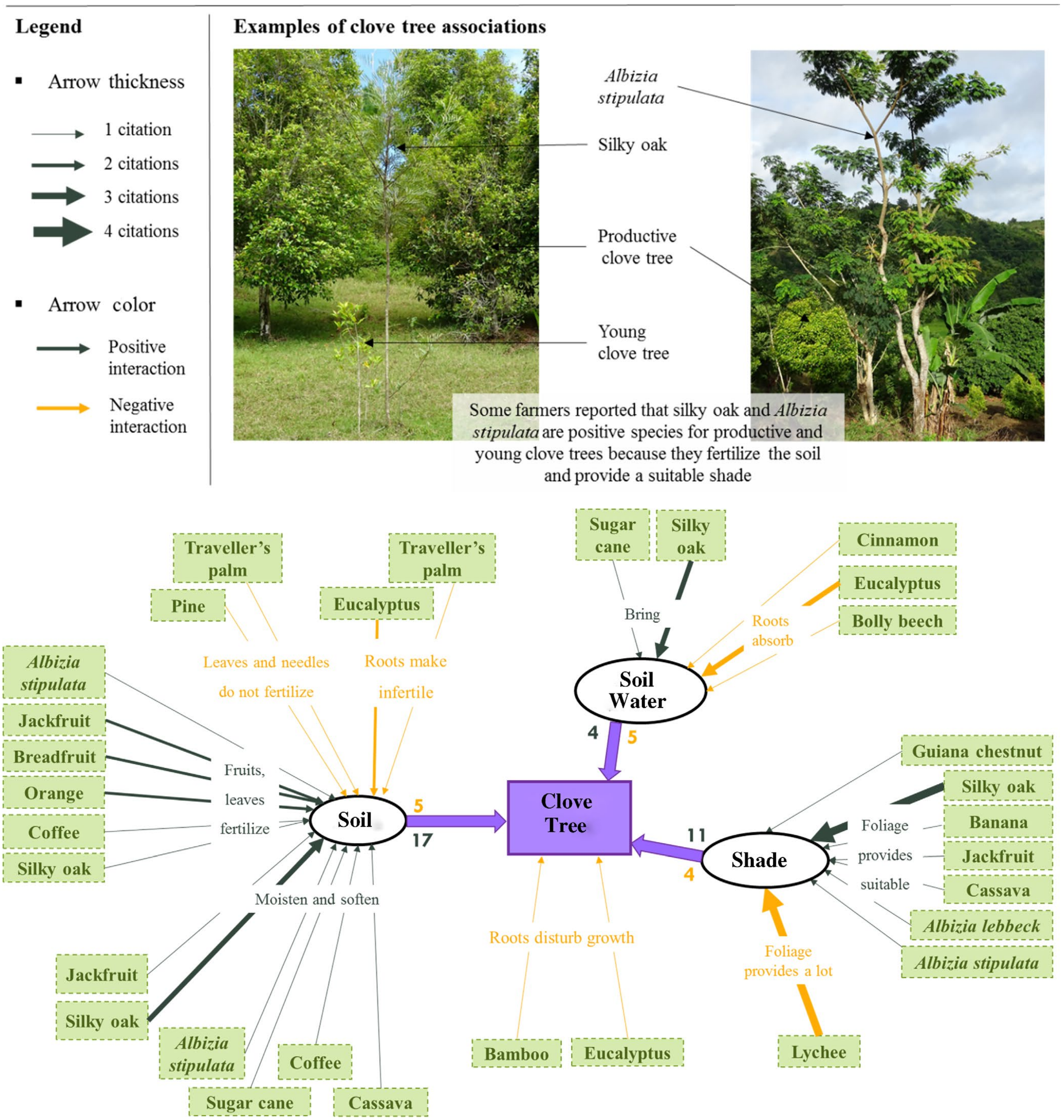


FIGURE 7 Cognitive map representing farmers' knowledge (17 farmers) concerning the positive and negative interactions of clove tree with other *tsabo* plant species, and the ecological processes involved in these interations

self-consumption, income generation, and the production of building material and firewood. Thus, the differences in the frequency of occurrence of the plant in *tsabo* are partly linked to their functions for the households, in particular, the diversity of fruit species. For instance, in addition to being highly appreciated as a fruit to eat, lychees have gained economic value since the improvement and the facilitation of lychee exports from Madagascar to Europe beginning in 1987 (Jahiel et al., 2014). The presence of banana, breadfruit and jackfruit in most clove-based *tsabo* is linked to their importance for human consumption, especially in the lean season, and as animal feed to cope with the lack of pastureland (pers. obs.). The pasture available for zebus is decreasing as farmers build gates around their *tsabo* to prevent other zebus from entering. Banana also has non-food uses: its leaves are used as decoration during traditional ceremonies and as plates for meals, and the central stem cut into pieces is used to add organic matter to the soil. Generally, these fruits are mainly produced for self-consumption due to the lack of access to profitable markets, the lack of collectors and motorised public transport in the village studied here, which require produce to be transported on foot over great distances. Even if coffee has largely lost its commercial value since the economic crisis in the 1970s, thereby affecting Malagasy coffee producers (Ruf & Blanc-Pamard, 1992), coffee trees were still observed in clove-based *tsabo* and harvests were sufficient to satisfy the low local consumption of Betsimisaraka people from villages and towns. Second, another driver is related to farm strategies, designed around the household's activities (agricultural or off-farm activities) and its assets and means of production (Bannister & Nair, 2003), and the infrastructure available to access markets (Bellow et al., 2008; Scales & Marsden, 2008). In our case, it appears that the plant agrobiodiversity in clove-based *tsabo* differs among farmers depending on the extent of paddy rice they cultivate, and the strategy they adopt to achieve household food self-sufficiency (pers. obs.). In fact, annual rice production cannot satisfy a household's needs if the rice fields are not large enough. In this case, farmers rely on the crops they grow in their *tsabo* to earn the cash they need to buy rice, and tend to increase the plantation of cash crops, and especially in agroforestry systems (Andriatsitohaina et al., 2020). Lastly, an important driver of *tsabo* plant agrobiodiversity is risk management. Cultivating a range of species with similar functions is a strategy to maintain these functions in the face of perturbations of different kinds, particularly climatic (cyclones) and economic (market price variations) disturbances. Thus, the presence and the abundance of a particular species in *tsabo* is largely driven by its sensitivity to different kinds of risk. One example of how the perception of risks affects farmers' agrobiodiversity choices was provided by vanilla, which was not planted by all the farmers despite its economic boom in 2016 (Llopis et al., 2019), or only in small proportions compared to other cash crops. The farmers' motivation to cultivate vanilla has been affected by the highly fluctuating sales price of vanilla (Llopis et al., 2019), problems of theft (Neimark et al., 2019) and the fear of not selling their production in a good formal market (Hänke et al., 2018). Another risk is linked to cyclones, which has led farmers to reduce the number of tall trees planted in association with clove trees, they may fall onto the clove trees and destroy the plantation.

Studying plant agrobiodiversity based on interviews with the farmers allowed us to identify the species that are important to the farmers, but the real plant richness of *tsabo* was probably underestimated, and this method of collecting data may have introduced some bias concerning the relative importance of the different species. For instance, the large number of tree species cited could be linked to the particular importance of trees for Malagasy people (Bing, 2018; Rafidison et al., 2020) or, alternatively, could be explained by the attentional mechanism of visual saliency, which makes some items stand out from their neighbours and immediately attract our attention. Conversely, the frequency of annual species, such as cassava or yam, was probably under-estimated, as these species were often observed during our visits to the *tsabo*, but were rarely mentioned by the farmers. One explanation for the apparent limited importance given to tuber species is their status as 'food-shortage' crops. Indeed, cassava and yam are usually consumed if rice was lacking in the lean period and are negatively associated with shortage, and the shame of not having enough rice to feed the family (pers. obs.). To check the real plant biodiversity in *tsabo*, flora inventories would enable more in-depth analysis and comparisons with other sites. The farmers interviewed did not mention the influence of development projects or government policies on how they managed plant agrobiodiversity. This may be due to the geographical isolation of the village we surveyed. However, several studies have shown that Malagasy government decisions drive farmers' strategies, for example, through the establishment of protected areas (Andriatsitohaina et al., 2020; Gardner et al., 2018).

4.2 | Farmers' knowledge of plant interactions drives species association practices

Analysis of the micro-zones revealed the existence of different types of species associations in clove-based *tsabo* that are explained by the map of interactions highlighting the ecological and agronomic intertwined functions of plant species. The farmers therefore incorporate their perceptions of the ecological interactions between species in their association practices. For instance, farmers reported that silky oak and jackfruit had two positive effects on mature clove trees by providing suitable shade and maintaining a degree of moisture in the soil thanks to the degradation of their fallen leaves, which improved soil fertility. Farmers' perception of such interactions explained the presence of jackfruit with clove in the two mixed clove age types and one of the two types of micro-zones containing young clove trees. Discussions with the farmers highlighted the positive impact of banana, Guiana chestnut *Pachira aquatica* and *Gliricidia sepium* on vanilla, by providing a favourable microclimate. This knowledge justified the presence of these three species in the micro-zones with a high density of vanilla.

Some species were found to co-occur in the same micro-zones, although some farmers reported that their association had a negative effect on one or both species. This was the case of coffee and clove, frequently seen associated with vanilla in two types of micro-zones (mixed age clove 1 and young clove 1), whereas some farmers reported that these two trees have negative effects on vanilla. Likewise, lychee trees were associated with clove trees in all four types of micro-zone, despite the farmers' perception that they cast too much shade. Traveller's palm was present in two types of micro-zones (mixed age clove 2 and young clove 2), although the farmers considered it has a negative effect on clove through its effect on the soil. Some authors also show that traveller's palm is a plant often linked to a degraded soil (Hladik et al., 2000) that suggests the palm would not be the cause of a degraded soil, but a consequence.

These examples of contradictions between knowledge and practices reveal how farmers manage trade-offs between the different ecological services and disservices provided by the species (Ango et al., 2014; Vaast & Somarriba, 2014). Depending on their preferences and their perceptions of interactions between species, farmers either choose to favour a given species over others or look for synergies (Carrière, 2002). This is often the case when the perceived interaction is that a given plant reduces the yield of another (especially a cash crop species), but otherwise provides numerous ecological services to the system (Ango et al., 2014). In a trade-off situation, farmers may choose not to plant a species because of its negative effects, but they may also decide to keep it and to change their practices to minimise its negative effects. One way of doing this is to modify the spatial organisation of the species within the system, as discussed later in this section.

Our study clearly identified the species that are most important to the farmers, along with the cropping practices and the knowledge associated with them. Yet, many species were only cited a few times and some knowledge was held only by one or a few farmers. Based on the hypothesis that such ecological knowledge can better explain contrasting and singular practices (Abric, 2011; Michel-Guillou & Moser, 2006), one possible solution would be to create mental maps at the individual scale that could be used to more finely represent farmers' knowledge and perceptions (Isaac et al., 2009; Vuillot et al., 2016), and in this way, to better understand the role of minor species, explain rare practices and also to focus more on the differences between farmers rather than on their similarities.

4.3 | Farmers' perceptions of the environment drive spatial organisation practices of agrobiodiversity

The topographical gradient at the scale of the *tsabo* and its consequences for the environmental characteristics (soil, moisture, exposure to sunlight and to cyclones) appear to structure the spatial organisation of plant agrobiodiversity, making it possible to provide growing conditions adapted to the needs of each plant species. The map of positive and negative interactions of clove trees reveals the attention paid by farmers to species water, fertility and light requirements, three factors which shape the biophysical heterogeneity of the environment. Analysis of the participatory *tsabo* maps highlighted common practices that can be explained by farmers' perception of the soil fertility, as reported in many ethno-pedological studies (Barrera-Bassols & Zinck, 2003) and through the catena concept developed by Milne and his colleagues in the 1930s to formalise farmers' perceptions of the spatial distribution of soils along a topographical gradient (Borden et al., 2020; Milne, 1947). Therefore, it appears that if the farmers favour the bottom of their *tsabo* to plant species such as vanilla or banana, it is because they know these species need fertile soil and moderate sunlight ('Vanilla is grown at the bottom of the *tsabo* where it is cool and humid (*mangatsiatsiaka*) as the sun heats that part less'). Bamboo is also left at the bottom because 'when it rains it retains water', thereby playing the role of a physical barrier against erosion. These biophysical considerations were also described in other studies dealing with the factors of land use change and management in the north of Madagascar (Andriatsitohaina et al., 2020; Ramboatiana et al., 2018). Our results provide an overview of the different environmental factors considered by farmers in their agrobiodiversity management practices. Soil appears to be a major factor, in the sense that farmers decide on the spatial location of a species according to its adaptability to soils of variable fertility. This suggests that managing plant species in space is a way for farmers to cope with soil heterogeneity, thereby confirming previous qualitative observations (Altieri, 2002). However, these exploratory results point to the need for a better understanding of farmers' knowledge of cultivated soils and their heterogeneity, and of relations between soil and plant agrobiodiversity (Niemeijer & Mazzucato, 2003).

The spatial organisation of species was also a response to trade-offs between ecological services and disservices that determine the way farmers distributed species relative to the location of the other species. This was notably the case for three useful species planted on the boundaries of *tsabo*: lychee, because its canopy casts too much shade over clove trees, eucalyptus (firewood, timber) because its 'hard roots' (*matoy vahatra*) take up water from the soil, competing with clove and vanilla, and the two bamboo species (land-use markers and construction materials) because their roots propagate quickly and begin competing with other species ('bamboo spreads quickly and can kill clove trees'). While farmers emphasised the ability of eucalyptus roots to 'dry out' the soil (Amazonas et al., 2018), its allelopathic effect on other species has also been proven (Chu et al., 2014), but not perceived by the farmers interviewed.

5 | CONCLUSION

By providing a better understanding of how farmers make and adapt their choice of plant species and the spatial organisation of the species by accounting for socio-economic and biophysical factors, our study contributes to fill the research gap on these understudied aspects of farmers/agrobiodiversity interactions. Such understanding is key to support the design of biodiversity-based solutions for enhancing the resilience of agroecosystems. In particular, our results emphasise the holistic perceptions that farmers have of the local environment, and the complexity of their decision-making, based on trade-off between the different functions of plant species and their effects on the environment. Our study hence highlights the importance of paying particular attention to farmers' knowledge and decision-making process concerning plant species choice and spatial organisation in development initiatives aiming at supporting agroforestry, as our results indicate that there is no 'one size fits all' agroforestry solution. For that, our findings and methods based on an emic and participatory approach pave the way for further interdisciplinary research on farmers/agrobiodiversity interactions, interweaving farmers' and researchers' knowledge through a 'multiple evidence base approach' (Tengö et al., 2014).

In Analanjirofo region, the change in land use from shifting cultivation to agroforestry offers promising prospects for the expansion of cash crop (e.g. clove tree, vanilla) based on win–win systems for food production, economic development and the ecosystem. In particular, agroforestry represents a way to restore land that was formerly forested, to limit erosion, regulate hydrological flows and restore soil fertility (Martin et al., 2020). The complex mosaic of land use observed in our study area results from farmers' decisions and constraints, in many places and over many years. In that sense, sustainable restoration of the landscape through agroforestry is not relevant without the close involvement of farmers and the full recognition and consideration for their knowledge.

In this context of ongoing agroforestry transition, initiated and driven by local Betsimisaraka people, our study highlights the high adaptability of farmers and the way they use opportunities to adapt to changes, which are the result of the interweaving of multiple knowledge and practices they observed and tested in situ (Berkes, 1999). Our results call for exploring the origin of—and changes in—local knowledge and factors that influence, weaken and/or enrich them, which would improve our understanding of the practices observed at a given moment in time and discuss their trends.

ACKNOWLEDGEMENTS

This work (ID 1702-022) was publicly funded by the ANR (the French National Research Agency) under the 'Investissements d'avenir' programme (ANR-10-LABX-001-01 Labex Agro) and coordinated by Agropolis Fondation in the frame of I-SITE MUSE (ANR-16-IDEX-0006). The authors thank the Occitanie Region (ALDOCT 000588, APAD project) and the Maison des Sciences de l'Homme of Montpellier (RADIPAM project) for their complementary financial support. They also thank the Dispositif de Recherches en Partenariat (CIRAD/FOFIFA/University of Antananarivo), Forêts et Biodiversité à Madagascar, for its logistic support. The authors thank the Isabelle Sanchez and Nicolas Verzelen for their help in the statistical analyses. The authors are particularly grateful for interpretation by Harcine Paul, for the friendly welcome by the villagers and the availability of the farmers interviewed. The authors thank Doyle Mckey for his thorough and constructive review of the manuscript. Finally, our thanks go to the two reviewers for their in-depth review that helped us significantly improve our article.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

AUTHORS' CONTRIBUTIONS

J.M., V.L. and S.M.C. designed the study; J.M. designed the methodology, collected and analysed the data; J.M., V.L. and S.M.C. led the writing of the manuscript; J.M., V.L., S.M.C., P.D., E.P. and V.R. critically reviewed the drafts and contributed to writing; V.L. is the project's PI.

DATA AVAILABILITY STATEMENT

The dataset is anonymised and stored on an open-source software: https://doi.org/10.18167/DVN1/IUM8PL (Mariel, 2021)

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Mariel, J., Carrière, S. M., Penot, E., Danthu, P., Rafidison, V., & Labeyrie, V. (2021). Exploring farmers' agrobiodiversity management practices and knowledge in clove agroforests of Madagascar. *People and Nature*, 00, 1–15. https://doi.org/10.1002/pan3.10238