Resource-Use Patterns in Swidden Farming Communities: Implications for the Resilience of Cassava Diversity

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Abstract Resource-use patterns, especially through exchanges among farmers, may ultimately confer resilience to the local agrobiodiversity. We investigated the use of cassava ethnovarieties by swidden farming communities in Brazil, exploring the structure of networks depicting farmers and the varieties they cultivate. The emergent nested resource-use pattern indicated that all farmers shared a core of top-ranked ethnovarieties (most common/abundant) while some farmers also cultivate rarer varieties. This pattern may result of individual preferences. Due to the current loss of interest and cultivation area for traditional agriculture, we simulated the extinction of crop fields to evaluate whether nestedness conferred robustness to cassava diversity. The diversity of ethnovarieties of cassava tended to be conserved when farmers were randomly removed from the network than when we preferentially removed farmers with more diverse crop fields. Stem cuttings of ethnovarieties are commonly exchanged among farmers, thus the extinction of ethnovarieties within crop fields could be restored. Therefore, we suggest that the interplay between the farmer's resource-use patterns and exchange system strengthens the resilience of cassava diversity, which is an important staple resource for such communities.

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Introduction

The development of techniques for managing the environment has always been part of the human socio-cultural context (Balée 2006). Swidden, or slash-and-burn, agriculture is regarded as one of the oldest farming systems, since hunter-gather societies progressively adapted to a sedentary life style (Piperno and Pearson 1998; Arroyo-Kalin 2010). Currently, this agriculture type is still practiced by human communities that manage tropical forests, such as indigenous and non-indigenous traditional communities of tropical countries (Peroni and Hanazaki 2002; Clement *et al*. 2010). Among the several crop species in this cultivation system, the cassava *Manihot esculenta* Crantz, in its diversity of ethnovarieties, is an important staple food for such communities (Clement *et al*. 2010).

Several management characteristics of swidden cultivation agriculture favored the high intraspecific diversity of cassava. Among them are: the development of a diverse soil seed bank over time, the increased opportunities for colonization of wild strains after vegetation removal, the establishment of new swidden vegetation plots, and the possibility of cross-breeding by planting different varieties in the same area (Peroni and Martins 2000; Martins 2005; Pujol *et al*. 2007). Additionally, recent studies emphasize the importance of social interactions among local farmers as an additional mechanism favoring high diversity of this resource (e.g. Emperaire

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and Eloy 2008). Local farming communities typically experiment with and propagate genetic materials through the exchange of agricultural resources. Such practice is a major dispersal force, establishing links among different swidden cultivation fields, and promoting opportunities for selection and cross-breeding, which ultimately result in higher regional agrobiodiversity (Emperaire and Peroni 2007).

This complex system of 'stakes' (cassava stem cuttings) exchange does not only promote diversity, but also helps to preserve the regional pool of cassava varieties (Emperaire and Eloy 2008) – here called ethnovarieties (i.e. varieties distinguished by local popular names). 'Stakes' are frequently exchanged with a farmer's parents and friends who cultivate different sets of varieties (Emperaire and Peroni 2007). Curiosity and desire to improve productivity drive the selection of new, morphologically different varieties (Boster 1985), which ultimately increase the local cassava diversity (Pujol *et al*. 2007).

The exchange of cassava is underpinned by two mechanisms: the farmer's social interaction patterns and their resource use patterns. The intricate system of social interactions among farmers will define how ethnovarieties are transmitted among the communities (cf. Pautasso *et al*. 2012). But more importantly, the way that farmers use the pool of cassava ethnovarieties will define the quality and quantity of the resource to be transmitted. For instance, due to individual preferences, some may cultivate all the ethnovarieties available regionally, while others may prefer only a few. Therefore, the resource use patterns of farmer communities could have important implications for the resilience of cassava diversity. For example, a cohesive social network of farmers would facilitate the regional dispersion of cassava, whereas communities maintaining highly diverse cultivation could possibly provide 'stakes' of all the available ethnovarieties. This combined effect would promote rapid recolonization, potentially overcoming local extinctions of any ethnovariety within the region. Consequently, some degree of resilience against local disturbances will be conferred to the pool of ethnovarieties (see Begossi 2006). The resilience of this farmer-cassava system also includes the social resilience, i.e. the ability of groups or communities to deal with external pressures as a result of social, political or environmental change (Adger 2000).

Therefore, a pertinent multidisciplinary challenge is to understand how farmer's networks and the use patterns of cassava ethnovarieties influence the robustness of such a staple resource in local human communities. Network theory is one of the methodological approaches to study these dynamics systems, and can be coupled with other methods such as ethnographic fieldwork, participatory approaches, spatial analysis at different levels, and computer simulations (Pautasso *et al*. 2012). In ecology, network thinking has been proven to be an efficient approach both to describe resource-use patterns (e.g. Araújo *et al*. 2008; Pires *et al*. 2011) and to provide solid inferences on the robustness of the system to extinction of its elements (e.g. Memmott *et al*. 2004; Mello *et al*. 2011). By illustrating the flow of knowledge and materials among communities (e.g., Janssen *et al*. 2006; Ramirez-Sanchez and Pinkerton 2009; Nolin 2010) the network formalism can also inform discussions on natural resource management and governance (e.g., Bodin *et al*. 2006; Bodin and Prell 2011). Here we studied the diversity of cassava ethnovarieties used by coastal farming communities of two distinct Brazilian regions. We integrated ethnographic fieldwork with network theory to investigate resource-use patterns and to infer how such patterns could confer robustness to the pool of ethnovarieties and resilience to the farmer-cassava system.

We first asked whether there were differences in the set of ethnovarieties used by farmers within each region. To this end, we evaluated the structure of the networks of the farmers connected to the cassava ethonovarieties cultivated, based on the following three hypothetical scenarios (Fig. 1). First, if farmers display different degrees of selectivity when using the ethnovarieties, a nested structure may emerge (Fig. 1a) (e.g., Araújo *et al*. 2010; Pires *et al*. 2011). This would mean that some farmers cultivate several ethnovarieties while others cultivate a predictable subset of these ethnovarieties. Second, if farmers show pronounced differences in their resource use, i.e., subgroups of farmers growing distinct subsets of the regionally available cassava ethnovarieties, the network would display a modular structure (Fig. 1b) (cf. Araújo *et al.* 2008). Such module division could plausibly emerge due the inherent differences in the spatial segregation and planting strategy of communities: in one region farmers used communal planting area, while another region is characterized by multiple household units. Third, if farmers do not show any preferences when using the local ethnovarieties, the network would not show any clear pattern (Fig. 1c). Finally, we infer the resilience of the agriculturally networked system promoted by the structure of the network depicting resource-use patterns. The farmer communities studied here live in the Atlantic Forest remnants, where protected area legislation prevents

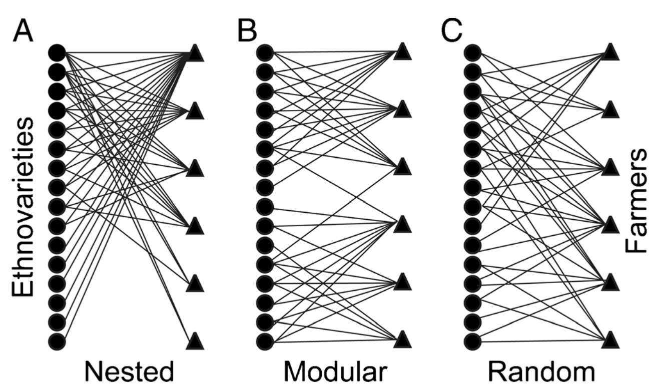

Fig. 1 Possible structure of the two-mode networks depicting farmer's communities (*triangles*) connected to the cassava ethnovarieties (*circles*) that they cultivate: **a** nested, **b** modular, **c** random

cassava cultivation. Given that traditional agricultural practices are being used in fewer cultivation areas due to a loss of popularity with farmers and pressures by environmental legislation, we asked how robust the regional pool of ethnovarieties would be by simulating the removal of farmers from this agriculturally networked system.

Material and Methods

Study Areas

We sampled 11 farmer communities in two areas in independent regions in Brazil, with distinct local history, agriculture management and phytophysiognomies (different structure of vegetation): the municipalities of Imbituba (state of Santa Catarina, southern Brazil) and Paraty (state of Rio de Janeiro, southeastern Brazil) (Fig. 2). Imbituba includes apredominant Restinga vegetation in a subtropical humid CFA Köppen climate. The local population has cultural traits of mixed indigenous people and Portuguese from the Island of Açores and Madeira due to the intensive Lusitanian migration in the mid-seventeenth century (Ferreira 2006; Lacerda 2003). Fishing and agriculture have been practiced since pre-Columbian time by the indigenous people and then immigrants (DeBlasis *et al*. 2007; Ferreira 2006; Lacerda 2003). In this region, five farming communities were sampled (Fig. 2a). All the fields are located in lowlands between the local dunes and the paleodunes. One distinctive characteristic of this region is that the local farmers establish their crop fields in a communal area (named *Areais da Ribanceira*). Based on local agreements, each farmer uses a 2- hectare cultivation field within the shared area. The cassava ethnovarieties are the main local resource; other crops include sweet potato (*Ipomea batatas* (L.) Lam.), yam (Dioscorea sp.), watermelon (*Citrullus lanatus* Schrad) and corn (*Zea mays* L.).

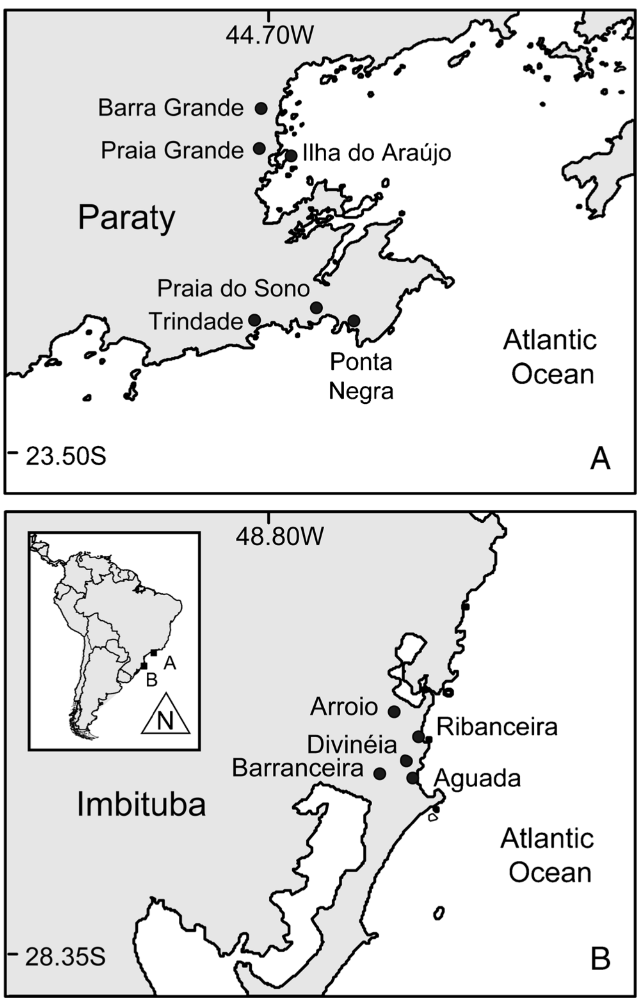

Fig. 2 The study areas and local cassava farming communities (*black circles*) in two distinct regions of the Brazilian coast: **a** Paraty, which is characterized by spatially segregated individual farming units, and **b** Imbituba, a shared communal farming area

Paraty is located in the coastal Atlantic Forest, although it also includes Restinga and mangroves, and the Köppen climate is AF, equatorial (Veloso *et al*. 1991). The local people, known as *Caiçaras*, are descendants of Tupinambá indigenous people, Portuguese and Africans who occupied the Atlantic forest in the region after 1500 (Begossi 2006; Adams 2000). The livelihood of this population has changed over time, but they still practice traditional fishing and swidden agriculture. Tourist services and the trade of extracted vegetable resources are smaller, but growing, economical activities (Begossi 2006; Hanazaki *et al*. 2007; Lopes 2009). We sampled six swidden agriculture-based communities in this region (Fig. 2b), located mainly along the hillside of *Serra do Mar*. In Paraty there is no communal cultivation area: all fields are individually established, i.e., household units, where activities are performed by both by men and women. The cassava flour is the main agricultural product, along with banana (Musa sp.), sugar cane (*Saccharum officinarum* L.), and palm trees.

Data Collection

We identified the 83 key participants by communicating with the local people using the "snow-ball" method (Bailey 1994). The participants were all farmers in the region who have cultivated cassava (*M. esculenta* Crantz) in the swidden agriculture system: 37 individuals from 5 communities in Imbituba (Arroio (2), Aguada (4), Barranceira (6), Ribanceira (10) and Divinéia (15)); and 46 individuals from 6 communities in Paraty (Praia do Sono (3), Ilha do Araújo (4), Praia Grande, Ponta Negra and Trindade (7), and Barra Grande (18)). We conducted interviews, under prior informed consent, to identify the current most important cassava ethnovarieties, as well as to understand the livelihood of farmers and the importance of the varieties for them. A free listing with no time limit was used to discover all cassava ethnovarieties that have been used for cultivation (Thompson and Juan 2006). Data sampling was carried out during May 2009 until January 2010 in Imbituba and in June and July 2010 in Paraty.

Data Analysis

To evaluate the differences in the use of the local resources, we calculated the frequency, ranking and salience (Thompson and Juan 2006) of mentioned cassava ethnovarieties with software Anthropac 4.0 (Borgatti 1992). Ranking refers to the order of ethnovariety citations and the salience index combines the ranking and frequency (Borgatti 1992). The ethnovarieties cited in the beginning of the free listing were assigned to the top ranking positions, whereas varieties cited later received low rankings. The rank and citation frequency of ethnovarieties were used to calculate the salience index, which suggests the importance of the varieties for the communities.

Because farmers from the two regions have distinct histories and cultural identities, the regions were analyzed independently. Resource-use interactions were described as two-mode networks, in which one set of nodes, representing individual farmers, were linked to other set of nodes representing cassava ethnovarieties that were mentioned during the interviews (Fig. 1). We inferred on the farmer's resource-use patterns describing the structure of these networks. First, we measured the degree of nestedness (Almeida-Neto *et al*. 2008). A nested network implies in heterogeneity in the use of resources, because not all farmers would use the entire pool of cassava ethnovarieties, i.e., some of them use many ethnovarieties, while others use a subset composed mainly the most cultivated ethnovarieties (Fig. 1a). Since the different cultivation strategies of farmers from Imbituba and Paraty regions may affect the exchange of ethnovarieties (Imbituba: communal cultivation area; Paraty: household fields), we investigated if local farmers were clustered due to the varieties that they use to evaluate the modularity of the network (Guimerà and Amaral 2005a, b). Here, a modular network would consist of weakly interlinked clusters of farmers that are internally strongly connected due to the use of the same resource (Fig. 1b). To allow comparisons of the different networks, we calculated relative nestedness (N*) and modularity (M*) (see Bascompte *et al*. 2003; Pires *et al*. 2011), and tested significances with a null model (cf. Bascompte *et al.* 2003). All technical details regarding network and null model analyses are available in the Appendix 1.

Resilience can be operationalized through the analysis of variables able to buffer perturbations (Berkes and Ross 2013). Here we use cassava diversity as one important variable related to the resilience of the cassava agricultural system. Thus, to infer the resilience of the system, we tested the robustness of the regional pool of cassava ethnovarieties to the reduction ("extinction") of local farmers in the communities. To accomplish this, we simulated the cumulative removal of individual farmers from one side of the network, and evaluated the magnitude of the secondary extinctions of ethnovarieties in the other side (cf. Mello *et al*. 2011). The removal of a local farmer mimics the loss of cultivation area or interest in the traditional swidden agriculture to more profitable activities (a current trend in the studied regions; Cavechia 2011). We simulated two removal scenarios, 100 times each: 1) removing farmers according to their degree (i.e. number of cultivated ethnovarieties), and 2) at random. Simulations were interpreted by plotting the average proportion of cumulative secondary extinction of ethnovarieties against the cumulative number of farmers removed. Details on the simulation experiment are available in the Appendix 2.

Results

Farmers who participated in this study were the few members of the communities who still carry on the local tradition of swidden cultivation. During the interviews, they demonstrated a deep knowledge about management of the land during the swidden cultivation agriculture. Farmers were aware of which cassava varieties are better suited to specific soil types at specific times of the year, and were also aware of the importance of maintaining cassava diversity. For example, the sweet varieties are used in short periods of harvest to be cultivated near their houses, while the bitter varieties are selected to produce cassava flour, and are cultivated exclusively in the swidden plots (as observed in other Caiçaras communities in the Atlantic Forest) (Emperaire and Peroni 2007). Different ethnovarieties supply the local demand for food, while also complying with individual preferences. Varieties with yellow or cream color are softer and usually cooked compared with the white and heavier varieties that are used to make flour because of their profitability and local market preferences. Farmers also choose varieties that are best adapted to the local environment: more resistant to the climate, plant disease or predators, and better suited to the poor soil fertility of the coastline in Atlantic Forest. The participants revealed that diversity is important not only to guarantee the cassava harvest, but also to buffer against chances events that could occur as the climate changes, and economic, social, political and agricultural changes take place.

In Imbituba, the 37 interviewed farmers (37 to 85 years old, mode=70) mentioned a total of 26 ethnovarieties of cassava. From these farmers, 10 ethnovarieties were mentioned more than 20 % of the time, representing the common regional resources. On the other hand, a similar number of ethnovarieties (12) were idiosyncratic (low salience indices), indicating that they were more rare resources restricted to a few fields (Table 1). In Paraty, the 46 farmers (32 to 82 years

Table 1 List of cassava ethnovarieties grown by the communities of Paraty (total citation n=266) and Imbituba (n=249)

Imbituba				Paraty			
Cassava ethnovariety local name	Frequency (%)	Rank	Salience	Cassava ethnovariety local name	Frequency (%)	Rank	Salience
Aipim eucalipto	85.7	1.5	0.76	Mandioca maricá	66.7	1.5	0.55
Mandioca torta	82.4	2.5	0.5	Aipim batubana	53.2	1.6	0.45
Mandioca franciscal	76.5	1.6	0.64	Aipim rosinha	44.7	1.9	0.34
Mandioca branca	64.7	2.6	0.38	Aipim manteiga	34	2.6	0.2
Mandioca amarela	52.9	2.8	0.31	Aipim preta	29.8	2.7	0.16
Aipim amarelo	48.6	3	0.24	Mandioca landi branco	28.6	1.7	0.21
Aipim pêssego	37.1	1.8	0.3	Mandioca loriana	28.6	2.3	0.15
Aipim roxo	34.3	2.5	0.2	Aipim nortista	19.1	2.6	0.11
Mandioca roxa	20.6	3.3	0.11	Mandioca bordão	19	1.5	0.16
Aipim manteiga	20	2.9	0.12	Aipim seda	14.9	2.4	0.09
Aipim branco	11.4	2.8	0.06	Mandioca tupã	14.3	2	0.09
Mandioca mandinga	5.9	1.5	0.06	Mandioca pauzinho	14.3	2	0.08
Mandioca sete casta	5.9	3.5	0.03	Aipim branquinha	12.8	2	0.1
Aipim timbó	5.7	4	0.03	Aipim vassourinha	12.8	2	0.08
Aipim Porto Alegre	5.7	3	0.02	Mandioca landi preto	9.5	1.5	0.08
Aipim vinho	2.9	2	0.03	Mandioca roxinha	9.5	2.5	0.07
Aipim abóbora	2.9	4	0.02	Mandioca mata fome	9.5	2	0.06
Aipim prata	2.9	6	0.01	Mandioca aipim preto	9.5	4	0.03
Aipim vassourinha	2.9	5	0.01	Aipim vermelha	8.5	1.3	0.08
Mandioca jaguaruna	2.9	1	0.03	Aipim Sinhá ta na mesa	8.5	2.3	0.05
Mandioca gauchinha	2.9	1	0.03	Aipim amarela	8.5	2.5	0.04
Mandioca mácula	2.9	4	0.02	Aipim roxinha	6.4	2.3	0.04
Mandioca vermelha	2.9	2	0.02	Aipim gambá	6.4	3.3	0.03
Mandioca folha redonda	2.9	3	0.02	Mandioca landi rosa	4.8	1	0.05
Mandioca bandi	2.9	6	0.01	Mandioca maranduba	4.8	1	0.05
Mandioca aipinzão	2.9	5	0.01	Mandioca landi	4.8	1	0.05
				Mandioca olhuda	4.8	3	0.03
				Aipim tupã	4.3	1.5	0.04
				Aipim vareta	4.3	2.5	0.02
				Aipim tapiruê	2.1	1	0.02
				Aipim da Bahia	2.1	2	0.02
				Aipim gema de ovo	2.1	2	0.01
				Mandioca tambaraçaba	2.1	2	0.01

old, mode=60), mentioned 33 ethnovarieties. Eight of the ethnovarieties were mentioned more than 20 % of the time, and four were idiosyncratic (Table 1). Compared to other traditional agriculture crops in Brazil (Emperaire and Peroni 2007), this diversity is considered relatively high.

The individual-resource networks of both regions showed a high nestedness degree (relative total NODF: Paraty N*= 0.459, p<0.001; Imbituba N*=0.648, p<0.001) (Fig. 3c), with a core of highly connected farmers and ethnovarieties (Fig. 3a and b). There were some farmers cultivating a high diversity of cassava ethnovarieties, while those who cultivated lower diversity tended to use the most common ethnovarieties. Such core of ethnovarieties was larger in Imbituba than Paraty (approximately 50 % frequency: Imbituba=6 ethnovarieties; Paraty=3 ethnovarieties; Table 1).

None of the networks displayed modular structure (relative Modularity: Paraty M*=−0.004, p=0.46; Imbituba M*=−0.206, p=0.999) (Fig. 2d). This indicated that in both regions the farmers presented high similarity in the use of cassava ethnovarieties.

The removal of farmers from the network resulted in an increase secondary "extinctions" of cassava ethnovarieties (Fig. 4a and b). However, ethnovarieties disappeared from the network approximately proportionally to the removal of farmers (a nearly linear relation), i.e. an intermediate case between a sudden and a slight "extinction" cascade.

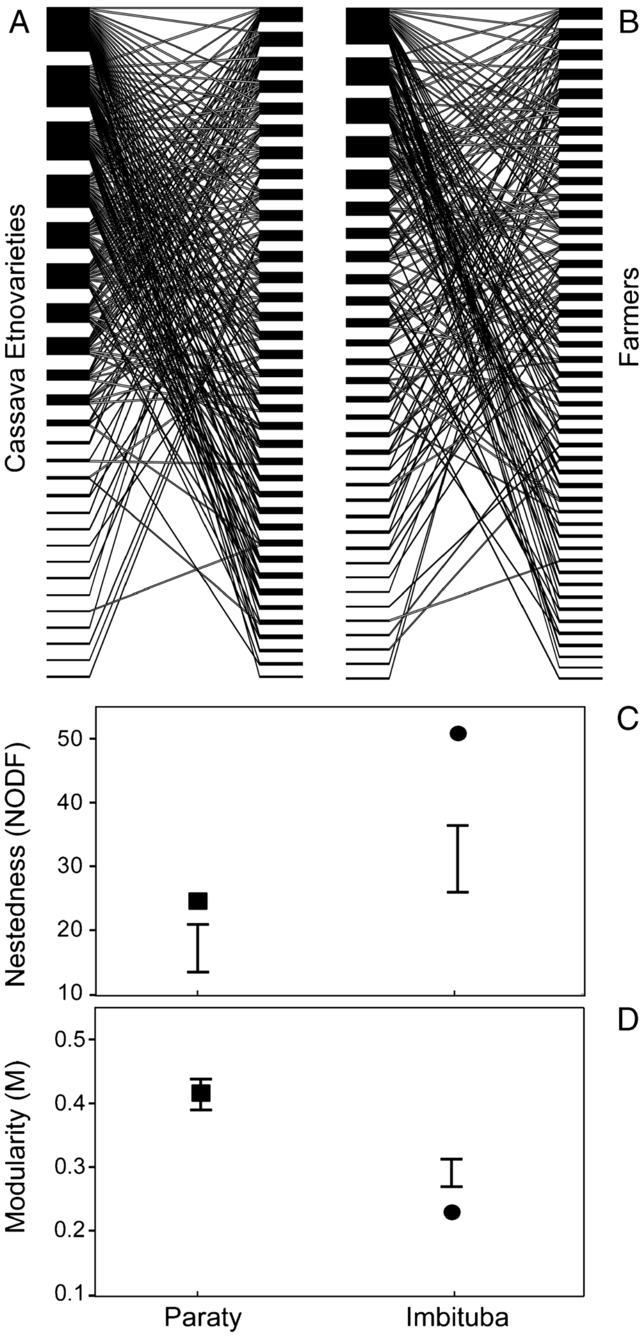

Fig. 3 Two-mode individual-resource networks depicting the cassava ethnovarieties (*left*) cultivated by the local farmers (*right*) in **a** Imbituba and **b** Paraty. In both regions, the networks were significantly highly nested **c** and less modular **d**. The whiskers represent the 95 % confidence intervals generated by a null model (see Appendix 1). The networks were generated with the Bipartite package (Dormann *et al*. 2008) using R software (R Development Core Team 2010)

Compared to the random removal scenario, the target removal of the farmers who cultivated more ethnovarieties impacted the network more significantly (Fig. 4a and b). These findings indicated that primary removal of farmers from the agricultural system could lead to secondary extinctions of ethnovarieties, but not in a very pronounced fashion. The agriculturally networked system displayed a degree of robustness, especially when farmer communities were removed at random.

Discussion

Our findings show that the local pool of cassava ethnovarieties is used in a hierarchical and shared manner among farmers within regional communities. This resource-use pattern is related to the individual preferences of local farmers and may confer some degree of resilience to the regional agrobiodiversity.

Farmers show remarkable different ranks of preference for cassava ethnovarieties (see also Peroni and Hanazaki 2002; Emperaire and Peroni 2007). Usually, farming communities share a group of common ethnovarieties that are often adapted to a wide range of environments and cultivate different rare ethnovarieties due to individual preferences. Our findings show that farmers display a peculiar pattern of resource use called nestedness (cf., Araújo *et al*. 2010; Pires *et al*. 2011) in both of the distinct, independent regions. In our context, the nested pattern indicates a differential use of the available pool of cassava varieties by farmers: there are farmers with more diverse crop fields than others who use fewer ethnovarieties. More distinctly, the set of varieties grown by the "more selective" farmers is an ordered subset of the pool grown by the "more generalist" farmers. The common ethnovarieties compose the top-ranked resources cultivated by both generalist and selective farmers, while the rare ethnovarieties tended to be grown only by the generalist ones.

Individual preferences and behavior are likely the mechanisms driving the emergence of the nested structure observed in the resource-use networks of the Paraty and Imbituba communities. The common cassava ethnovarieties are cultivated by most farmers because of their high performance in different environments and because traditional management practices promote their use (see Fraser and Clements 2008; Calvet-Mir *et al*. 2012) in each region (plan land in Imbituba; slopes in Paraty). Common ethnovarieties are preferably used to supply the demand of cassava flour because they can be processed together, which guarantees the annual production and reduces unpredictability and risk. Rare ethnovarieties are usually not well established, not adapted to wider environmental conditions, or the result of gradual exchanges among farmers. These ethnovarieties are used to meet specific demands under the control and experimentation of individual farmers (see Peroni and Hanazaki 2002; Emperaire and Peroni 2007). The choice for the specific rare ethnovarieties is driven by the curiosity of farmers -usually the generalist ones- who experiment and test new varieties on their field crops. We cannot, however, discard the complementary hypothesis that rare varieties can also result from the seed bank germination

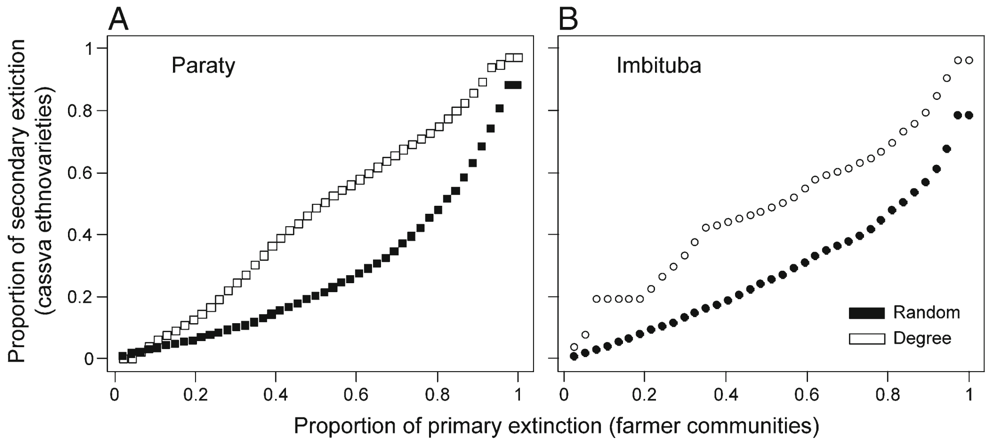

Fig. 4 Robustness of the regional pool of cassava ethnovarieties to the simulation of the cumulative extinction of the farmers. Primary extinctions represent the cumulative removal of the farmers from the regional networks, and secondary extinctions represent the consequent disappearance of ethnovarieties. The removal of the farming communities was simulated under two scenarios: at random and according to the farmer's number of cultivated ethnovarieties (*degree*). In both cases, random removal triggered a less pronounced extinction curve

and were assimilated by the few farmers who have manipulated this phenomenon (Peroni 2004; Pujol *et al*. 2007).

The common use of the local top-ranked ethnovarieties has led to a high resemblance in resource-use patterns among farmers. High similarity in the use of cassava ethnovarieties was expected in Imbituba due to the use of a set of cassava ethnovarieties adapted to the communal cultivation area. Because in Imbituba farmers from different communities share the crop area, the spatial proximity was expected to favor more social contact and therefore a higher probability of exchange. Even though the local farming communities in Paraty traditionally use individual crop fields (the family household units) that are widespread (see Fig. 2a), such spatial segregation does not led to distinct local preferences for some ethnovarieties, as observed among isolated communities in Central Africa (Deletrê *et al.* 2011).

The high diversity of this agricultural resource is the product of long-term local experimentation and selection (see also Emperaire and Peroni 2007). The preservation of such diverse cultural heritage is an important concern in face of the local socio-political context of the region. In the studied areas, recent socio-political changes may be a source of disturbance to the agricultural system (see also Folke *et al.* 2010). In both Imbituba and Paraty, the regional agrobiodiversity pool depends on the few local actors and community-based organizations who still undertake traditional farming activities. Currently, these swidden farming communities suffer expropriation or limitations in the use of their areas for housing and planting due to real estate interests or because they are settled within restrictive protected areas. Traditional practices have also been replaced by more attractive or profitable activities or have declined due to the gradual loss of territory for cultivation, which resulted in remarkable loss of local ethnovarieties (Peroni and Hanazaki 2002; Assis 2007; Begossi *et al.* 2006). An additional concern to this resource is the loss of land due to political land-use policies and governmental incentive for monoculture, which has also been seen in other countries (Fu *et al*. 2005; Nautiyal *et al*. 2008). Reducing planting area threatens the traditional cultural values and local crop varieties (Nautiyal *et al*. 2008). For example, with the present reduction of approximately 80 % of the planting area available in the Imbituba region, the loss of varieties is already a real concern (Cavechia 2011). Our simulated extinction scenarios provide important clues to evaluate the robustness of the cassava diversity and of the farmers-cassava system.

The robustness of a networked system is highly dependent on its structure (Albert *et al*. 2000), and seems to increase with the degree of nestedness (Piazzon *et al*. 2011). Likewise the robustness of the agricultural system studied here is subjected to how farmers use the cassava ethnovarieties. In the socio-ecological context, interactions between socio-economic (farming practices) and physical components (biodiversity) determine the system's ability to deal with disturbances (Schouten *et al*. 2013). Using a metapopulation analogy, we suggest that the crop fields can be seen as favorable habitats where the ethnovarieties are dispersed through the exchange system, and can colonize (when planted by farmers), go extinct (when they are lost), and be recolonized (see Peroni 2004). In this context, habitats (crop fields) are linked in a networked resource system (Parrott *et al*. 2012). Therefore, by removing farmers from the networks depicting resource-use, we simulated extinction of crop fields and found a nearly constant increase in the consequent extinctions of cassava ethnovarieties.

In our simulations, no sudden cascade of secondary extinctions of varieties was triggered; therefore we considered the agricultural system relatively robust. In other words, when farmers are cumulatively removed at random, most ethnovarieties still remain available in the pool. The robustness of the cassava agricultural system is created by the overlap in the resource-use, represented by the nested pattern. Since a common subset of ethnovarieties is cultivated by all communities, only a few rare ethnovarieties tend to be extinct. Such robustness to random removals is typical of networks within which most elements have few interactions while only a few display a disproportionally high number of interactions (Albert *et al*. 2000). However, the same pattern makes natural systems more vulnerable to target removals (Memmott *et al.* 2004; Bastolla *et al*. 2009; Mello *et al*. 2011). When we preferentially removed the more generalist farmers in our simulations, the extinction curves increased more quickly, indicating that the agricultural systems are more sensible to the extinction of crop fields of the farmers who cultivated higher diversity of cassava. This represents the worst case scenario with the communities growing the rare ethnovarieties becoming extinct and causing irreversible depletions in the regional agrobiodiversity pool. These findings reinforce the need for strengthening farmer communitie's organizations and public policies for in situ (on farm) conservation (Thijssen *et al*. 2013).

The robustness of the cassava agricultural system to the loss of its elements allows us to infer on the resilience of such an important staple resource (see also Begossi 2006). In our context, resilience as the capacity to absorb disturbances (e.g., Holling and Gunderson 2001) means that local extinction or eventual loss of a given ethnovariety can be restored. One may note that crop fields are not static as the network depiction. A fundamental dynamic that can be embedded in the network structure of human communities is the trade of agricultural resources (see Emperaire *et al*. 2008). Indeed, such exchange networks are important components of on-farm conservation of agrobiodiversity (Calvet-Mir *et al*. 2012). Therefore, the mechanism behind such restoration is the exchange system of cassava 'stakes', which essentially occur during social interactions among the members of different communities. Rare and common varieties could be potentially available to all farming communities, because varieties can be dispersed through a dense network of social relationships. Nowadays there is a lack public policies favoring conservation of agrobiodiversity in Brazil. While governmental institutions do not play a significant role, local farmer's crop fields and community-based organizations working at local regional scales are the primary agents maintaining the local agrobiodiversity. We highlight that the traditional exchange system among farmers is the main relevant source of new cassava ethnovarieties.

While local diversity and the exchange system of ethnovarieties seem to be the important factors influencing the dispersal process (see Holling 2001), this process also depends on the how that farmers are organized within their community, and the external influence of governmental and non-governamental organizations (Isaac and Dawoe 2011). Social interactions are spatially dependent and dependent of a political organization of local farmers (Pautasso *et al*. 2012). Thus, the inherent differences between the cultivation strategy and spatial distribution of our studied cases could ultimately affect the social interaction probabilities. Since individuals that are physically closer are more prone to interact, we expect that aggregation of crop fields within the communal area of Imbituba would favor a very cohesive social system linked to the existence of a farmer community-based organization in Imbituba that do not exist in Paraty. Because dense social systems can prevent fragmentation of a cultivated population (see Janssen *et al*. 2006), we suggest that ultimately local extinctions of ethnovarieties in Imbituba could be potentially restored. On the other hand, the family units of the Paraty farmers, which present a clear spatial segregation, would lead to lower probabilities, or rates, of social interactions, consequently forestalling the ethnovariety exchange and hindering the restoration of locally extinct ethnovarieties. For that reason, we suggest that cassava ethnovariety pool of Paraty is less resilient against local disturbances than the Imbituba one. Indeed, many cassava ethnovarieties have been already lost in the southeastern Atlantic Rainforest region, where Paraty is located (Peroni and Hanazaki 2002), thus the depletion of the pool of cassava genetic diversity could be dramatic in the next several years.

The communities of Paraty are particularly vulnerable: they are inserted in an arena of political conflicts, where governmental agencies or individuals associated with top-down protected areas or environmental legislation have driven local communities to stop their traditional activities, such as fishing (Begossi *et al*. 2011; Lopes *et al*. 2013) and farming. Therefore, our study can inform legislators to restructure priorities regarding the conservation of the agrobiodiversity.

Conclusions

By describing the structure of an agricultural networked system, we elucidate the main dynamics of cassava agrobiodiversity. We suggest that the resource-use patterns of swidden farming communities could ultimately result in resilience to the loss in diversity of this important staple resource. The nested pattern of the farmers-ethnovarieties interactions reveals the co-existence of "more generalist" and "more selective" farmers, which confers a degree of robustness to the pool of regional cassava ethnovarieties. Since one important mechanism for restoring locally extinct ethnovarieties is the social interactions among farmers, we suggest that possible differences in the cohesion of the exchange system will confer different levels of resilience these regions.

Our findings further suggest that farmers contribute to the preservation and enlargement of the agrobiodiversity over time. Farmers become the real agents responsible for this diversity, and conservation efforts should focus on the processes that generate agricultural diversity (Louette 2000). Putting the exchange networks in the context of agricultural biodiversity would be an effective approach to understand the factors that maintain diversity among farmers. Our findings link the dynamics of an agricultural system with the in situ (on farm) conservation of crop varieties (see Pautasso *et al*. 2012). This connection can potentially help the involved parties create more cohesive conservation strategies, and should encourage resource managers to work together with local farming communities to minimize environmental and socioeconomics impacts (see Marshall and Marshall 2007). Finally, these results highlight the importance of the farmer-cassava system "as a whole" in the maintenance of biological, agricultural and cultural diversity.

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Appendix 1. Network Analysis

Individual-resource interactions were described as two-mode networks (e.g., Pires *et al*. 2011) in which the nodes representing local farmers were linked to other nodes representing the cassava ethnovarieties mentioned in the interviews. These individual-resource networks were plotted in an incidence matrix A to depict the interactions between the cassava ethnovarieties (rows) and local farmers (columns), where element aij of the matrix is 1 if ethnovariety j was cultivated by farmer i and zero if otherwise. We measured the degree of nestedness and modularity to describe the structure of the individual-resource networks.

Nestedness (N) is a particular network property in which the interactions are asymmetric, with a core of densely connected nodes and other less connected nodes that generally interact only with the core (e.g., Bascompte *et al*. 2003; Guimarães *et al*. 2006). In our case, nestedness may reveal heterogeneity among resource use: not all farmers use the entire regional pool of cassava ethnovarieties, i.e., some use mostly of the ethnovarieties available, whereas others use only the most cultivated ones. We calculated the degree of nestedness using the nestedness metric based on overlap and decrease fill (NODF, Almeida-Neto *et al*. 2008) using ANINHADO 3.0 software (Guimarães and Guimarães 2006). In highly nested matrices, NODF has a tendency to reach 1; otherwise it tends to be zero.

The farmers of Imbituba and Paraty regions differ in their cultivation strategies (Imbituba, communal; Paraty, household fields) and these differences may have an impact on the ethnovariety exchanges. Therefore, we evaluated whether the local farmers were clustered due to the varieties that they use. To do so, we evaluated the modularity of the networks. Modularity (M) quantifies the tendency of the nodes to cluster into cohesive groups: M measures the difference between the number of interactions among nodes that are within modules and the number that are between modules (e.g. Guimerà and Amaral 2005a, b). A modular network in our case would consist of weakly interlinked groups of farmers that are internally strongly connected due to the use of the same resource (e.g., Olesen *et al*. 2007). In other words, we would see high homogeneity of resource-use inside groups of farmers and high heterogeneity between them. We calculated M using a simulated annealing algorithm to identify the partition of a network into modules that yields the largest degree of modularity with the NETCARTO program (Guimerà *et al*. 2004).

Since the regional networks are different in size, i.e., the number of nodes and links, we used the relative nestedness (N*; see Bascompte *et al*. 2003) and relative modularity (M*; see Pires *et al*. 2011) to allow cross-network comparisons. The relative nestedness is defined as $N^* = \left(N - \overline{N}_R\right) / \overline{N}_R$, where N is the observed nestedness and is the average nestedness of random matrices generated from the null model analysis (see below). Similarly, the relative modularity is defined as $M^* = \left(M - \overline{M}_R\right) / \overline{M}_R$ (see Pires *et al*. 2011).

The significance of the network metrics was evaluated using the null model approach. Random networks were generated by a null model that shuffled the original total of 1 s among new matrix cells according to the frequency of citations of each ethnovariety (marginal totals of rows) and the number of ethnovarieties grown by each local farmer (sum of columns). Thus, each cell has different probabilities of being filled according to the two features of the observed dataset (see null model 2 in Bascompte *et al*. 2003): $c_{ij} = \frac{1}{2}\left(\frac{Pi}{C} + \frac{Pj}{R}\right)$, where Pi=the number of farmers that cultivate ethnovariety i (row sums); Pj=the number of ethnovarieties cultivated by farmer j (column sums); C=the number of local farmers (columns); and the R=number of cassava ethnovarieties (rows). The empirical values of nestedness and modularity were evaluated by checking whether the observed values were within the 95 % confidence intervals generated by the 1,000 randomized networks. The relative nestedness and modularity were evaluated by the z-score; the p-value was calculated as the proportion of randomized values that were higher than the observed values.

Appendix 2. Removal Simulation

To infer on the resilience of the cassava agricultural system, we tested the robustness of the regional pool of cassava ethnovarieties to the extinction of farmers from the communities. To accomplish that, we cumulatively removed farmers from one side of the network, and evaluated the magnitude of the secondary extinctions of ethnovarieties in the other side (cf. Mello *et al*. 2011). The removal of a local farmer mimics the loss of cultivation area or interest in the traditional swidden agriculture for to more profitable activities (a current trend in the studied regions; Cavechia 2011).

We simulated two scenarios: the removal of farmers according to their degree (i.e. number of interactions representing the diversity of cultivated ethnovarieties), and random removal. In the former, we removed the farmers sequentially from those with more interactions (i.e. cultivating more ethnovarieties) to those with fewer interactions. The latter was our benchmark, when all the farmers had the same probability of being removed from the network (i.e. abandon the agriculture practice). To incorporate uncertainty, we repeated the simulations 100 times for each region and used the average proportion of secondary "extinctions". Simulations were interpreted through extinction curves, generated by plotting the average proportion of cumulative secondary extinction of ethnovarieties against the cumulative number of farmers removed. A positive relationship between primary and secondary extinction is expected in all cases: a extinction curve increasing slightly would represent a very robust network, because more farmers would have to be removed to extinct few ethnovarieties; accordingly, a curve with a very sharp increase would represent a very fragile network, in which the removal of few farmers would trigger the extinction of several ethnovarieties. The simulations were performed using package bipartite for R environment (Dormann *et al*. 2008).

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