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RESEARCH ARTICLE

Scenarios for an agroecological transition of smallholder family farmers: a case study in Guadeloupe

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Abstract

In Guadeloupe, a French overseas region, civil society is calling for an agroecological transition (AET) to obtain access to healthy agricultural products following a major ecological scandal caused by a persistent pesticide that contaminated water and agricultural soils. To support such a transition, we tested a five-step methodological framework designed to enable farmers to describe and explore scenarios in farming systems, socio-technical systems, and social-ecological systems. This is one of the first operational methodological tools to build scenarios and action plans for an AET taking into account simultaneous changes in these three systems. We first surveyed 63 farmers and positioned their farming systems along an AET gradient using the Efficiency-Substitution-Redesign framework. In the second step, a sub-sample of 18 farmers, who represented diverse farming system types, individually defined AET scenarios at the level of their own farms. We then applied a farm simulation model to evaluate the technical and economic performance of each scenario. The third step involved analyzing the types of social networks used by 45 farmers to share information and promote technical, commercial, and social exchanges to implement agroecological practices in their territory. In the fourth step, we worked with a group of 15 farmers and 10 researchers in a participatory workshop to characterize the natural resources, their associated services and disservices, and the actors involved. In the last step, the farmers and researchers defined an action plan for the AET in their territory. Our results suggest that AET is understood by farmers to be a gradual and multiscale process involving the co-creation of knowledge, technical solutions, and organizational changes. An initial outcome of the process tested was a shift in the stance of researchers. Their focus shifted from experiments conducted on-station toward experiments managed by farmers to co-produce knowledge on the viability of agroecological practices under their own specific conditions, triggering discussions between stakeholders (such as advisers, policy makers, smallholders, and larger farmers) in the territory.

Keywords Participatory research · Agroecological practices · Ex-ante assessment · Social-ecological system · Socio-technical system

1 Introduction

The production-oriented model of agriculture promoted in Europe after World War II, and through the Green Revolution in Asia, Latin America, and Africa, was based on the use of synthetic inputs (fertilizers and pesticides), and the increased use of irrigation, mechanization, and genetics (Duru et al. 2015a; Nicholls et al. 2016). This model has come under increasing criticism due to its negative effects on biodiversity, ecosystem functioning, climate change, product quality, and human health, as well as the increasing scarcity of fossil resources (IAASTD 2009; MEA 2005). Agroecology

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is increasingly presented as an alternative to this production-oriented model of agriculture. While multiple definitions of agroecology have been proposed in recent years, there is a consensus that agroecology embraces three elements: a transdisciplinary science, a set of practices, and a social movement (FAO 2019; HLPE 2019; Wezel et al. 2020). As a transdisciplinary science, agroecology involves the integrative study of the ecology of a food system, encompassing ecological, economic, and social dimensions (Francis et al. 2003). Authors have identified diverse pathways for an agroecological transition (AET). These range from farming systems that use agricultural inputs more efficiently and redesigned systems that rely on biodiversity (Hill 1998; Nicholls et al. 2016) to the transformation of entire food systems (Gliessman 2016). Duru et al. (2015a) showed that to design biodiversity-based agricultural systems, changes are required at three levels, namely the farming system, the socio-technical system, and the social-ecological system.

A farming system corresponds to the links between a farmer's objectives, the structure of the farm (labor, animals, equipment, capital including the use of natural resources such as land, water, and biodiversity), the set of decisions used to manage the production process, and the performance of crop and livestock sub-systems (Capillon 1993; Osty 1978). The socio-technical system integrates (1) the niche where radical innovations emerge, (2) the socio-technical regime, corresponding to the locus of established practices and associated rules that stabilize existing systems (e.g., technology, user groups and practices, markets, industry structure, policy), and (3) the broader socio-technical landscape, which influences niche and regime dynamics (demographical trends, political ideologies, societal values, prices, and macro-economic patterns) (Geels 2002, 2011). The social-ecological system can be defined as the links between (1) a social system, composed of users, managers, and governance institutions that use technologies and infrastructure to manage artificial and natural resources and allows the management of natural resources at the local level (e.g., landscape or watershed), and (2) a complex ecological system or ecosystem generating these natural resources (Duru et al. 2015a).

Participatory scenario development and visioning are commonly used in applied agricultural research, from land use and territorial planning to climate change adaptation and governance of water resources, among others (Andreotti et al. 2020; Bourgeois et al. 2017; Vergragt and Quist 2011; Voinov and Bousquet 2010 to cite just a few examples). Only a few studies propose operational methods to support the definition of scenarios for an AET involving significant system transformations at various scales. For example, Pissonnier et al. (2019) propose a modeling tool to help farmers define transformative AET scenarios at the farm scale. These scenarios involve a redesign of the farm to decrease the use of pesticides; however, the authors mention the need to consider changes beyond the farm scale, particularly collaborations between different farmers. At the territorial scale, Della Rossa et al. (2022) combine socio-technical analysis, innovative design, and serious game to describe lock-ins to the adoption of agroecological innovations and explore alternatives. Barnaud et al. (2018) operationalize the concept of ecosystem services through participatory action research processes. They emphasize the social-ecological system by highlighting social interdependencies between and within users and providers of ecosystem services to define levers of collective action in an AET perspective. These approaches complement tools that guide individual decision-making.

As socio-technical and social-ecological systems can support or impede the application of individual practices, methods and tools are needed that can connect changes in practices to changes in these systems to achieve an AET. Our study proposes an operational method to guide farmers, individually and collectively, in the definition of scenarios for an AET involving changes in farming systems, socio-technical systems, and social-ecological systems.

The study was conducted in the northern part of the Caribbean island of Guadeloupe, a French overseas region. Over the past few decades, the use of a persistent pesticide called chlordecone in banana cropping systems grown in the southern part of the island has led to the contamination of almost one-third of agricultural soils and associated food systems (Crabit et al. 2016; Lesueur Jannoyer et al. 2016). This public health problem has prompted questions regarding the production-oriented and export-driven agricultural model pursued in the region. As a consequence, farmers in the northern part of the island, where banana has not been grown, and where soils have hence not been contaminated, are under pressure from civil society to transition toward sustainable practices in order to produce healthy products for the whole region (Ozier-Lafontaine et al. 2018). Such a context was well suited for testing with farmers and research scientists a method to develop AET scenarios and key elements for an action plan that takes into account interdependencies between farming, socio-technical, and social-ecological systems at the territorial scale (Fig. 1).

After describing the study site, we present the main steps of the method and its application. We then discuss the lessons learned for developing AET scenarios and action plans in the study site and the strength and limitations of the method for supporting effective change.

2 Methods

2.1 Study site

The study was conducted in Nord Grande Terre, located in the northern part of Guadeloupe (16° 24′ 22.449″ north 61° 28′

Fig. 1 Participatory workshop to co-design with farmers an action plan for agroecological transition at the territory level.

7.157″ west), where five districts (Le Moule, Petit Canal, Anse Bertrand, Morne à l'Eau, and Port Louis) pooled their skills and resources in 2014 to implement more ambitious intercommunal projects. With an area of 324 km^2, 58,267 inhabitants, and 2,400 farms, this territory represents the main agricultural area of the island (40% of the agricultural area of Guadeloupe).

The tropical climate is characterized by two main seasons: the dry season (January to April) and the rainy season (July to October). They are separated by two transition periods (Météo France 2022). Temperatures remain stable and mild throughout the year, from 20 to 29 °C on average, depending on the altitude.

The limestone plateau of the area, despite an average rainfall of 2300 mm per year, regularly experiences periods of drought. Given that the soils are not contaminated by chlordecone, there is a high demand for crop and animal products from this territory (Fig. 2).

The Nord Grande Terre territory's economy is driven mainly by agriculture, and particularly sugar cane production, the main crop, which is grown in the plains by both smallholder farmers and large companies and then transformed by a sugar processing plant. Sugar cane was introduced in the area during the French colonial period. After Guadeloupe became a French department in 1946 and a series of land reforms were implemented (from 1967 to 1993), access to irrigation, mineral inputs, and mechanization (through machinery sharing cooperatives) was promoted. The land reforms also permitted the development of various agricultural cooperatives managed by farmers' organizations that facilitate access to inputs and subsidies.

In the lowland areas of Nord Grande Terre, tubers, roots, and vegetables are cultivated for home consumption and sale in local markets mostly by smallholder farmers, and melon is cultivated for export, in this case mostly by large companies. Non-cultivable areas, temporary grasslands, and crop residues (sugar cane stems) are used to feed cattle.

As observed elsewhere in Guadeloupe, smallholder farms (defined as having a standard gross output of less than EUR 25,000 per year) contribute considerably to the production of agricultural goods and services, and represent 90% of the total number of farms in the study area (Agreste 2022). However, smallholder farmers do not always meet the administrative criteria used by various agricultural services to be formally identified as farmers. Indeed, as most of them engage in multiple economic activities, they are rarely officially registered as farmers, and consequently are not eligible for government social welfare services reserved for farmers. They may receive support or aid from the sugar cane sector when they are affiliated with a farmers group. However, other crops dedicated to the local market are poorly structured and poorly supported by public services.

2.2 Methodological framework

In the pilot experiment described here, we aimed to give smallholder family farmers an opportunity to receive recognition for their role in the production and management of multiple resources, and voice their points of view as freely as possible without the presence of economic or political representatives.

The proposed method for developing AET scenarios and action plans with farmers considers three analytical systems:

– Farming system
– Socio-technical system
– Social-ecological system

For each analytical system, our team, consisting of researchers from agronomy, animal sciences, economics, sociology, and anthropology, explored existing methods and tools to define individual and collective scenarios of change with farmers.

To define scenarios for an AET that integrate shifts in farming systems, socio-technical systems, and social-ecological systems, we devised the five-step method described below (Fig. 3). The five steps were conducted between February 2018 and March 2019. The first outcomes of the process were monitored between April 2019 and December 2020.

Step 1: Positioning farming systems along an AET gradient

The aim of the first step, conducted from February to May 2018, was to characterize smallholder family farm diversity and to position farms on an AET gradient. This served as the basis to describe existing systems and develop farm-scale scenarios in step 2, working on the assumption that farmers would envision more or less transformative technical changes

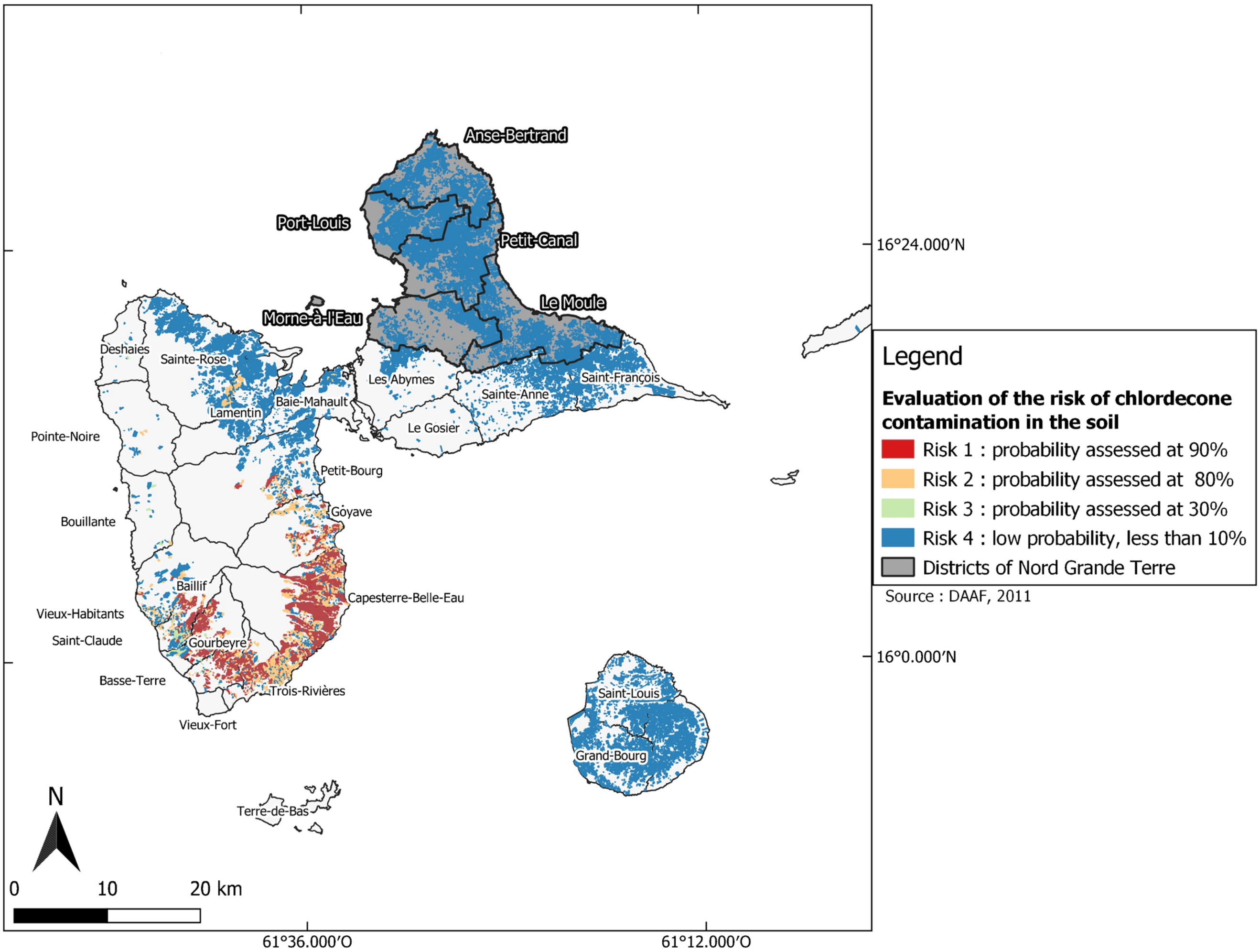

Fig. 2 Location of the study site: the Nord Grande Terre.

depending on their location along this AET gradient. This was also the basis to describe the specific socio-technical networks used by farmers in step 3.

At the farm scale, frameworks such as the Efficiency-Substitution-Redesign framework proposed by Hill (1998) are used to locate farming systems along an AET gradient (Duru et al. 2015b; Nicholls et al. 2016). This framework makes a distinction between (1) the efficiency stage, characterized by changes in conventional systems to reduce the consumption and waste of costly and scarce resources (e.g., optimal timing of operations and doses of fertilizers); (2) the substitution stage, where environmentally disruptive inputs are replaced by those that are more environmentally benign (e.g., purchase of organic fertilizers instead of mineral fertilizers); and (3) the redesign stage, where design and management approaches are implemented to rely more heavily on ecological processes and ecosystem services than on external inputs. For Duru et al. (2015b) or Gliessman (2016), the two first stages correspond to a weak transition and a technocentric form of agriculture that does not break with the dependence of industrial inputs and monoculture practices. The redesign stage corresponds to a conversion of the farm based on agroecological principles such as the enhancement of agroecosystem diversity, soil, and animal health.

As many smallholder farmers in the region are not registered on public administration lists because they are not formally considered to be farmers, we used non-random snowballing sampling (Laws et al. 2013) to identify 63 farmers (around 12 for each of the five districts in the study site), meaning that a first survey was used to identify more farmers to be surveyed, and so on. In order to know where to locate these 63 farms along the AET gradient, each farmer responded to an individual questionnaire with open-ended questions concerning the structure of their farm (labor, areas of the crops, and size of the various animal herds) and their crop and livestock sub-system management practices (tillage, management of soil fertility, pests and diseases, recycling or not of crop or animal products). Drawing from their answers and the work of Hill (1998), we identified four AET locations: (1) conventional farms using exclusively synthetic inputs, (2) efficient farms that are decreasing their amounts of synthetic inputs, (3) farms that aim to substitute their synthetic inputs with purchased organic inputs,

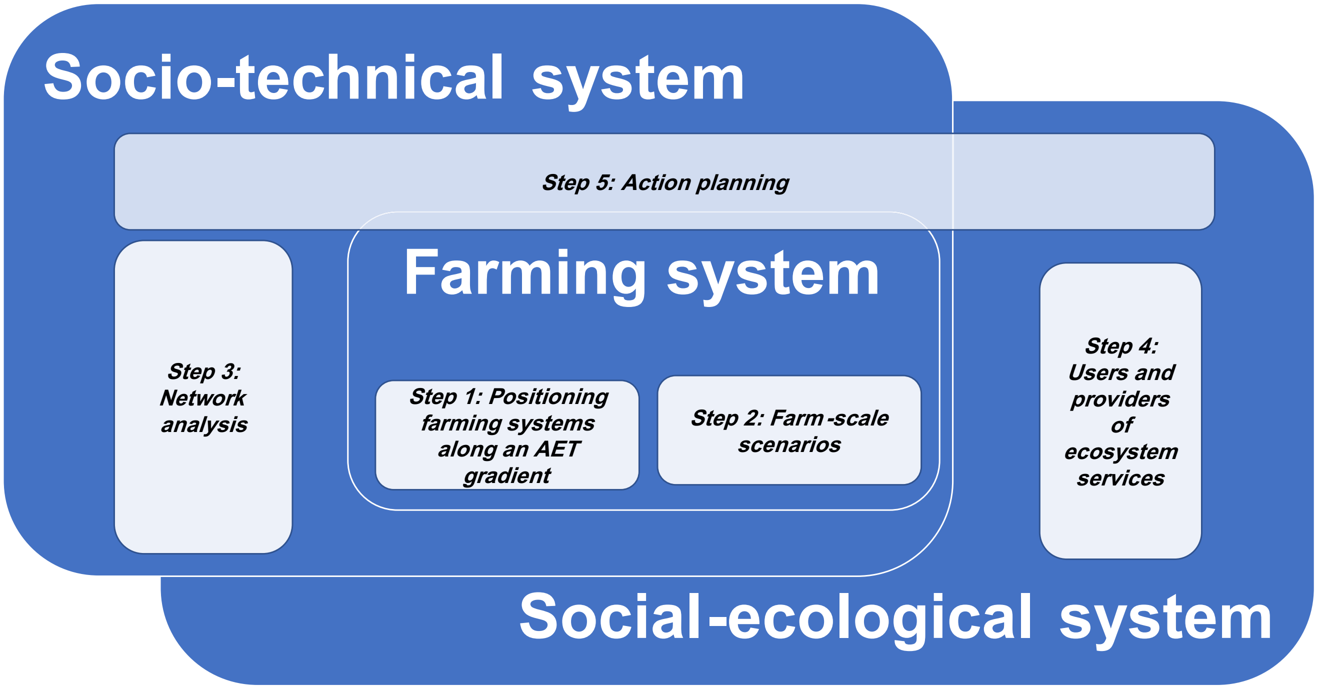

Fig. 3 The five-step methodological framework to enable farmers to explore scenarios in farming systems, socio-technical systems, and social-ecological systems.

and (4) agroecological farms whose production sub-systems rely on agroecological principles at the farm scale (farm diversification, recycling of crop and animal biomass and nutrients, low or no use of synthetic inputs). We then located each of the farms in the sample along this gradient.

Step 2: Farm-scale scenarios

The aim of this step was to support the definition by farmers of scenarios of changes to transition toward sustainable practices at the farm scale. Out of the 63 farmers in step 1, we selected a sub-sample of 18 farmers who represented farmers at various locations along the AET gradient. They were selected on a voluntary basis and for their willingness to implement changes in their farms. In a first survey conducted in May 2018, we collected data on their current situation (S0-size and management of the crop and livestock sub-systems) and on a scenario of changes (S1) they would like to implement in their farm, whether or not the scenario was based on agroecological principles. To build the scenarios, farmers could define any change in their crop and livestock sub-systems regarding the amount of input use, nature and size of the sub-systems, and management practices. Farm-scale scenarios were simulated and compared through a whole-farm simulation model. Whole-farm simulation models can be useful since they permit the redesign of a farm to be considered (Pissonnier et al. 2019). Sempore et al. (2015) showed that simple models which calculate the supply and demand of mineral, fodder, or cash resources are more suited to formulate and assess technical alternatives at the farm scale in a participatory exercise than optimization models or more complex rule-based simulation models. In these approaches, the biophysical processes, and particularly the yields obtained under a diversity of management practices or pedo-climatic conditions, are not simulated but are inputs of the models based on expert knowledge (from farmers, advisers, and researchers), the literature, or experimental databases (Le Gal et al. 2022). We used a model developed for the Guadeloupe region which considers the various crop and livestock systems that may be found in the diversified farms of the region. The tool calculates different aggregated indicators at the farm scale such as biomass production (Eq. 1), total cost of inputs (Eq. 2), income (Eq. 3), or gross margin per hectare (Eq. 4) and per man day (Eq. 5) (Rasse et al. 2018).

$$\text{Farm biomass production} = \left(\sum_{\text{crop }1}^{\text{crop }n}\text{Production} + \sum_{\text{Animal }1}^{\text{Animal }n}\text{Animal weight}\right) \div \text{Farm area} \quad (1)$$

$$\text{Cost of Inputs} = \sum_{\text{crop } 1}^{\text{Crop } n}(\text{Cost of fertilizers} + \text{Cost of pesticides} + \text{Cost of seeds}) + \sum_{\text{Animal } 1}^{\text{Animal } n}(\text{Cost of feed} + \text{Veterinary care cost}) \tag{2}$$

$$\text{Income} = \sum_{\text{crop } 1}^{\text{Crop } n}(\text{Gross added value} - \text{Equipment cost} - \text{Cost of labour} + \text{Subsidies}) + \sum_{\text{Animal } 1}^{\text{Animal } n}(\text{Gross added value} - \text{Equipment cost} - \text{Cost of labour} + \text{Subsidies}) \tag{3}$$

$$\text{Gross added Value per ha} = \left(\sum_{\text{crop } 1}^{\text{crop } n}\text{Amount sold} \times \text{Sale price} - \text{Cost of inputs}\right) + \left(\sum_{\text{animal } 1}^{\text{animal } n}\text{Number sold} \times \text{Sale price} - \text{Cost of inputs}\right) \div \text{Farm area} \tag{4}$$

$$\text{Gross added Value per man day} = \text{Gross added value per ha} \times \text{Farm area} \div \text{Total number of working days} \tag{5}$$

We simulated the combination of changes in input supply, crop/livestock management practices, and crop/livestock type and size that farmers wanted to explore by changing the associated input variables of the tool. The tool was then used for a multicriteria assessment of these changes.

In a second survey conducted in July 2018, we presented and discussed with the farmer the results of the comparative analysis of scenarios, and in particular whether the scenario of changes actually supports his or her AET.

Step 3: Network analysis

To describe the socio-technical system in which the farms would be embedded, we used social network analysis (SNA). SNA makes it possible to understand and highlight interactions and knowledge flows between actors (Chaudhury et al. 2017; Isaac 2012; Newman 2003). Information networks play a key role in the adoption of technologies and innovative practices, and in addressing environmental change in agricultural systems (Chaudhury et al. 2017; Isaac 2012; Maertens and Barrett 2013). First, we set out to identify the key actors already supporting agroecological practices in the five districts. The targeted agroecological practices were the ones mentioned in steps 2 and 3 by farmers that followed the agroecological principles of diversification, recycling of nutriments and biomass, soil, and animal health (Wezel et al. 2020). To do so, between June and August 2018, we collected social network data through a semi-structured questionnaire with 45 farmers from the initial list of 63 farmers in step 1 (around 8 to 10 farmers for each of the five districts in the study site). They were different from the ones that participated in step 2 in order to avoid involving the same farmers in too many surveys. This allowed us to identify which actors were specifically supporting the agroecological practices under investigation. We categorized the support and related connections in three categories corresponding to those most frequently mentioned:

- Information-sharing connections (including thematic meetings and training programs, formal, informal, mandatory, or voluntary)
- Social connections (including not only family exchanges but also services known in Creole as “*koudmen*,” which consist of providing help without expecting help in return)
- Commercial connections (including the barter of plants, cuttings, fruits, vegetables, animals)

Using Pajek software (Batagelj and Mrvar 2016; De Nooy et al. 2018), we measured the number and type of connections for each farmer (centrality) in order to establish the importance of stakeholders in the network (those mentioned most frequently by farmers), as proposed by Chaudhury et al. (2017). The identification of these connections and of the key promoters of AET provided the basis for discussions in the participatory workshop carried out in step 4 to characterize the social-ecological system.

Step 4: Users and providers of ecosystem services

The objective of this step was to characterize the social-ecological system in which the farms were embedded from the point of view of the farmers themselves. We followed the operational proposition developed by Barnaud et al. (2018). It allows one to highlight existing interdependencies between actors involved in the provision and use of ecosystem services and disservices in order to guide collective decision-making. We asked farmers to identify these (dis)services of natural resources at the territory scale and the actors involved as users and providers.

This analysis was carried out in March 2019 during a 1.5-day workshop with 15 farmers who represented the diversity of farms identified in step 1. They were selected among representatives of key agricultural actors (particularly cooperatives for the use of agricultural equipment and associations selling agroecological products) promoting the AET in the territory identified in step 3. Ten scientists engaged in action research on the AET in the study site participated to provide their own perception of the issues analyzed and to fine-tune their research activities to farmers' needs and context. The first two authors of this publication facilitated the proceedings without being participants in the process.

Following Barnaud et al. (2018), we elicited a shared representation of the social-ecological system through collective mapping. First, we built a common understanding of the word "resource" to use it accordingly during the workshop. In a plenary session, a list was drawn up of the meanings which participants gave to this word by gathering answers to the question "which resources are key to your agricultural activity?" The answers then were organized into natural, human, financial, material, and cultural categories by the facilitators, who validated their classification with participants.

We then asked each participant to come to a wall displaying a large piece of paper presenting a drawing of the geographical limits of the territory. After introducing themselves, the participants located their farm on the map and wrote down their main activity (agricultural or not), and their main agricultural production system. They then located on the map the natural resources and agricultural infrastructure identified in the previous listing.

Subsequently, participants formed two groups, one with farmers and one with researchers, to be able to compare their points of view, but also to partially address information and power asymmetries that can emerge in such situations (Barnaud et al. 2016). Both groups described perceived associated services and disservices of each resource identified in the listing, and the discussions that went beyond the services were annotated on the table developed for this purpose (e.g., issues of traditional knowledge loss, technical changes occurred around the use of a resource over time, the introduction of new diseases). Finally, both groups drew social network maps related to two resources identified as key (water and soil): the diversity of actors involved in providing and using them, and the interactions these actors have in relation with the resource.

Step 5: Action planning

The aim of the final step, conducted in March 2019, was to define an action plan to support an AET from the point of view of farmers, taking into account the outputs of steps 1 to 4. The participatory approach to build ex-ante impact pathways proposed by Blundo-Canto et al. (2018a) was adapted for this purpose. The approach, developed for the strategic planning of research for development projects, highlights the systemic changes (e.g., in knowledge, capacity, motivation, practices, interactions, and behavior of actors) that the participating group deems desirable to reach impact at scale. Starting from a vision of a desirable future state (10-year timeframe), the participants define which actors would need to make a change to achieve it and how, why currently they do not do this (obstacles to change), or what pushes them to do this change (opportunities), and finally what strategies (actions) should be put in place to allow the actors to undertake these changes.

On the second day of the workshop, participating farmers were asked to discuss what a shared 10-year vision for their territory would look like in connection to agriculture. Based on the conclusions on services, disservices, and actors at the territory scale made in step 4, a slogan synthesizing a positive vision for the territory was collectively defined. Diverging views were discussed and compromises made to reach a shared vision. The participants then were separated into two groups to allow for more active participation of all present. Participants were asked to define the changes in practices, interactions, and behavior needed to achieve this vision, and the associated changes in knowledge, capacity, motivation, and organization required. The agroecological practices identified in steps 1 and 2 were used to trigger the reflection on these changes. We then discussed the barriers to these changes, and the potential actions that different actors would need to carry out to remove these barriers at the territorial level. The results of the workshop were published in a workshop report and distributed to participants, and are being used as an input to plan and reassess participatory action research activities.

It is important to emphasize that the action plan is a broad guideline and that the work of defining it does not end with step 5. After the workshop, actors interested in building new projects based on this action plan come together to define a concrete proposal and look for funding resources. In our case, the objective was to provide the basis for an action research project that would go beyond technological solutions to tackle more systemic transformations needed to achieve the AET.

3 Results and discussion

3.1 Farm diversity along an AET gradient

A single farm could have diverse cropping and livestock subsystems, and the farmer might apply agroecological principles in some but not all of them. For instance, sugar cane cropping systems are usually managed in a conventional manner, whereas agroecological principles are applied in arboriculture, apiculture, gardening, and livestock sub-systems. According to the type and amount of inputs used, the level of diversification of the farm, and the recycling or not of biomass, 23% of the 63 farms surveyed were considered to be conventional (type 1), 20% corresponded to ones where farmers had changed practices to be more efficient in their use of synthetic inputs (type 2), 34% were combining cropping/livestock systems under conventional and agroecological management but mostly with the aim to substitute synthetic inputs by organic inputs (type 3), and 23% were fully agroecological (type 4).

Type 1 conventional farms had an average area of 10 ha. They generally were producing sugar cane with deep tillage and chemical control of weeds. Sugar cane was associated in some cases with cattle rearing using traditional management practices (animals tethered to stakes), but without integration between these two systems. Type 2 farms also were producing sugar cane, but they were implementing management practices (fertigation or mechanical weeding) to decrease or render more efficient the use of synthetic inputs. Farms had an average area of 2.5 ha. Type 3 farms corresponded to more diversified systems, with the main area cropped with sugar cane and an additional area generally dedicated to vegetable gardening managed under agroecological practices (recycling of biomass and nutrients, low use of synthetic fertilizers, intercropping of species), as well as some cattle managed in the traditional mode. The farms had an average area of 5 ha. The agroecological systems in type 4 were diversified, with more than five crops integrated with animal husbandry (crop sub-products used for animal feeding, animal manure used on crops). These farms had an average area of 4 ha.

For the four types of farms, activities were mostly conducted by a single farmer. The use of service providers was common for soil tillage and harvests for sugar cane cropping systems.

The specificity of the AET in the context of Guadeloupe lies in the co-existence of different agricultural production models, for example agriculture dedicated to local markets and home consumption alongside agriculture dedicated to exports to mainland France (Angeon and Hoarau 2015). Such a co-existence can be observed in a same farm where conventional and agroecological practices are implemented. Indeed, farmers cannot always use agroecological practices throughout the system (Fanchone et al. 2020) and tend to preferentially implement them on food crops.

By emphasizing smallholder farmers, who are much more diverse than generally described, our typology consequently complements existing ones that have demonstrated the coexistence of different agricultural models in Guadeloupe (Stark et al. 2016; Fanchone et al. 2020).

The description of the existing systems confirmed that management practices of smallholder farmers differed according to their location along an AET gradient. This is linked to their objectives regarding AET. For type 1 farmers, who have not yet adopted agroecological principles, an AET would have to be driven by the sugar cane sector. The sugar processing plant, farmers' cooperatives, and technical institutes could help support this transformation. They actually developed a "sustainable sugar cane program" that funded an experiment involving agroecological practices (cover plants, new planting techniques). However, it did not include financial mechanisms to promote the change in farmers' practices. Type 2 farmers, who are in the first stage of the AET gradient, have started to implement technical changes that are mostly driven by their wish to decrease their production costs. Type 3 farmers are already engaged in this AET, but face challenges in the diversification of their farms and the integration of its various subcomponents. For type 4 farmers, who are fully engaged in agroecology, the challenge is mostly to improve farm performance.

3.2 Scenarios of change at the farm scale

The simulation tool was proposed to farmers to test various combinations of changes (Table 1). The main change farmers chose to test was a decrease in the amount of synthetic inputs; however, the changes they wanted to test and their associated results were related to the extent of the transition envisaged by the farmers. Most farmers envisioned a gradual transition from a conventional to a more efficient farming system, or to a system in which synthetic inputs were replaced with organic ones (biopesticides, cover plant). None of them proposed a radical change from a conventional/efficient farming system to an agroecological farming system. Farmers already considered being agroecological (farmers 13 and 15) tested changes permitting improved biomass production (which was generally lower than that obtained by conventional farmers) while strengthening the livestock sub-system; they were also interested in new modes of commercializing products.

With the exception of exploring new modes of product commercialization, we were able to simulate scenarios combining the various changes proposed by farmers (Table 1). Our simulations showed that agroecological farms presented lower performances in terms of farm gross product (1020 euro·ha year^{-1} versus 3376 euro·ha year $^{-1}$) and biomass production (2.9 versus 4.8 t·ha year $^{-1}$), but had a higher gross margin per workday than conventional farmers (63 versus 24 euro·man day $^{-1}$). This was mostly explained by the fact that agroecological systems had lower synthetic input costs than conventional systems. Additionally, the agroecological farmers (type 4) did not mention a significantly higher number of working days. This may be explained by the specific nature of the agroecological farms that participated in this step, with a high proportion of semi-perennial crops, namely yam (*Dioscorea alata*), madere (*Colocasia esculenta*), cassava (*Manihot esculenta*), plantain banana (*Musa paradisiaca*), and sweet potato (*Ipomoea batatas*). Moreover, a sense of work being meaningful in agroecological systems also may lead to an underestimation of the amount of work invested in farming activities (Bezner Kerr et al. 2022), particularly if this work is assumed by non-paid family member.

Figure 4 represents the results simulated by the tool for the current situation of a farm (S0) and the changes envisaged by

Table 1 Scenarios simulated by farmers at farm scale (with C, conventional farms; E, efficient farms; S, substitution farms; A, agroecological farms). †S: substitution, ‡C: conventional, §E: efficient, |A: agroecological.

	Farmers																		Total
Types	S†	S	S	C‡	C	C	S	S	E§	E	C	S	A|	S	A	C	E	C	
Farm number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Decrease in the amount of synthetic inputs	x	x	x	x	x	x	x	x	x	x	x					x	x	x	14
Introduction of a new cropping/livestock system		x	x	x		x							x	x	x	x	x	x	10
Introduction of a new agronomic practice			x	x		x	x	x		x			x		x		x	x	10
Increase in animal number	x			x		x		x	x						x	x	x		8
Purchase of new equipment		x	x			x							x	x	x		x		7
Organizational change at farm level	x	x	x			x	x		x	x									7
New mode of commercialization of products	x					x					x		x	x	x			x	7
Increase/decrease in cropping area	x			x				x	x	x		x							6
Biodiversity increase		x				x											x		3

the farmer (S1). It highlights the main transition pathways tested by farmers. For instance, farmer "6," who grows sugar cane on 0.75 ha and raises cattle (7 animals) and goats (8 animals), aims to transition from a conventional management of sugar cane by replacing synthetic fertilizers with organic fertilizers. He also aims to increase the number of cattle (+5 animals) and to introduce a small market gardening activity (0.15 ha) using compost to avoid the use of mineral fertilizers. The introduction of a market gardening activity in the production system demonstrates a search for a higher diversification

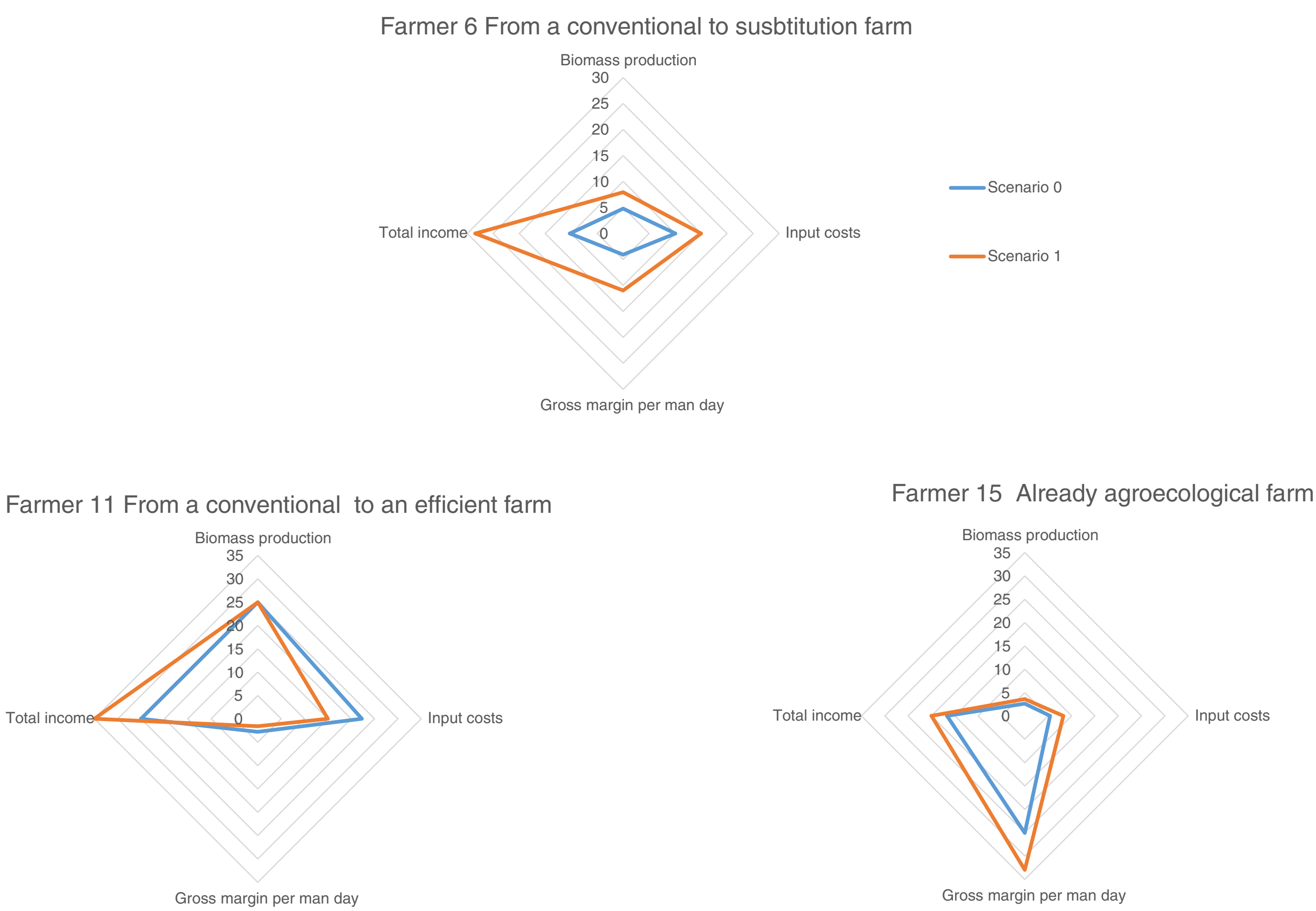

Fig. 4 Simulated performances for farms along different transition pathways (scenario 0 being the baseline, and scenario 1, the changes proposed by the farmers).

of the farm, but the compost is purchased rather than produced through a closer integration with his livestock systems. This scenario led to an increase in biomass production and income at the farm scale permitted by the cattle and gardening activities. Farmer “11,” who grows sugar cane on 1 ha, and tomato and lettuce on 0.2 ha, and raises cattle (7 animals), is representative of a search for a more efficient use of synthetic fertilizers. He aims to improve the efficiency of inputs through fertigation. This scenario led to a decrease in the consumption of inputs and an increase in income. Farmer “15,” growing yam on 0.35 ha, madere on 0.5 ha, malanga on 1 ha, and cassava on 1 ha, and intercropping banana with sweet potato on 0.012 ha, as well as raising cattle (15 animals), pigs (3 animals), and broilers (4 animals), was considered already agroecological. He plans to produce vermicompost, double the area of madere, and increase poultry production (25 animals). Here the increase of poultry production is highly related to the need to produce more compost and increase the area of madere, highlighting the integration of crop and livestock systems. This scenario led to an increase in total income permitted by the poultry activity.

This second step helped farmers to explore the specific combinations of changes that they wanted and their estimated effects on farm performances. As shown by Sempore et al. (2015) and Pissonnier et al. (2019), the benefit of using a whole-farm modeling tool does not lie in the accuracy of its predictive power but rather in its capacity to support discussion on the combinations of technical changes to render it possible to engage in an AET pathway. Here modeling helped farmers assess the importance of engaging or of strengthening the diversification of their farms. It also helped them to identify whether or not these changes would support an AET.

This study showed that at the individual level, farmers preferred AET scenarios based on the introduction of practices that allow the reduction of commercial inputs through better efficiency and substitution. Few farmers proposed a redesign of their farms. Deffontaines et al. (2020) highlighted that changes implemented by farmers are compatible with an existing socio-technical system. Farmers consequently proposed what they found realistic to be implemented on their farms and did not think outside the box. It seems that for this scenario, obstacles at the level of the territory involving access to resources may also explain why farmers initially were so prudent.

3.3 Socio-technical environment at the territory scale

The results of the third step of our framework showed that there is a juxtaposition of various technical networks, namely the commercial, social, and information connections associated with the technical changes identified in the previous step (Fig. 5A). Farmers navigate through these juxtaposed networks according to the specific issues they need to address. Some actors are only linked to farmers by a specific connection, whereas others have multiple links and are part of various networks. This is for example the case of peers, farmer groups, or cooperatives that are part of the three technical networks.

Through network analysis, we identified key actors who already promote the main agroecological practices mentioned by farmers in step 2 (scenario development), such as intercropping, mulching, crop rotation, green fertilizers, and low tillage. Older farmers appear to be most active in promoting practices such as intercropping, mulching, and crop rotation. Farmers also mentioned the Internet as a driver in their implementation of agroecological practices, particularly for new practices such as low tillage (Fig. 5B). This demonstrates the importance for farmers to navigate between networks but also to combine various knowledge sources.

This step also revealed that agroecological farmers presented the highest number of connections with their socio-technical environment (Fig. 5C), highlighting the importance of these connections for the implementation of agroecology, and that AET has a strong social component that cannot be addressed at the farm scale.

Many authors mentioned the role of peers and older farmers as holders of endogenous knowledge on agroecological practices and are consequently key actors for this transition (Darré 1991; Della Rossa et al. 2020). This importance of peers and older farmers, as well as the Internet, also may be explained in our context by the lower connections of smallholder farmers with public institutions. However, low connections with public institutions do not mean that no connection exists since the agroecological farmers were the most connected ones. Della Rossa et al. (2020) highlighted that diversified farms in Martinique (another French oversea region) received weak support for developing technical skills but had more room for agroecological innovations compared to farmers embedded in more formal supply chains.

Many authors have shown that AETs are situated processes embedded in a territory (Berthet et al. 2015; Duru et al. 2015b). They are based on material and immaterial interactions (beliefs, modes and coordination of actors, socialization, and learning processes) which are melted together on the site (Hakmi and Zaoual 2008).

3.4 Social-ecological system

In the participatory workshop, farmers mapped the natural resources and agricultural infrastructure in the territory and the associated ecosystem services and disservices for their agricultural systems. The starting point was to define, for each resource identified in the mapping exercise, the benefits and disadvantages generated by their use or valorization. For example, they identified the diverse water resources (rill,

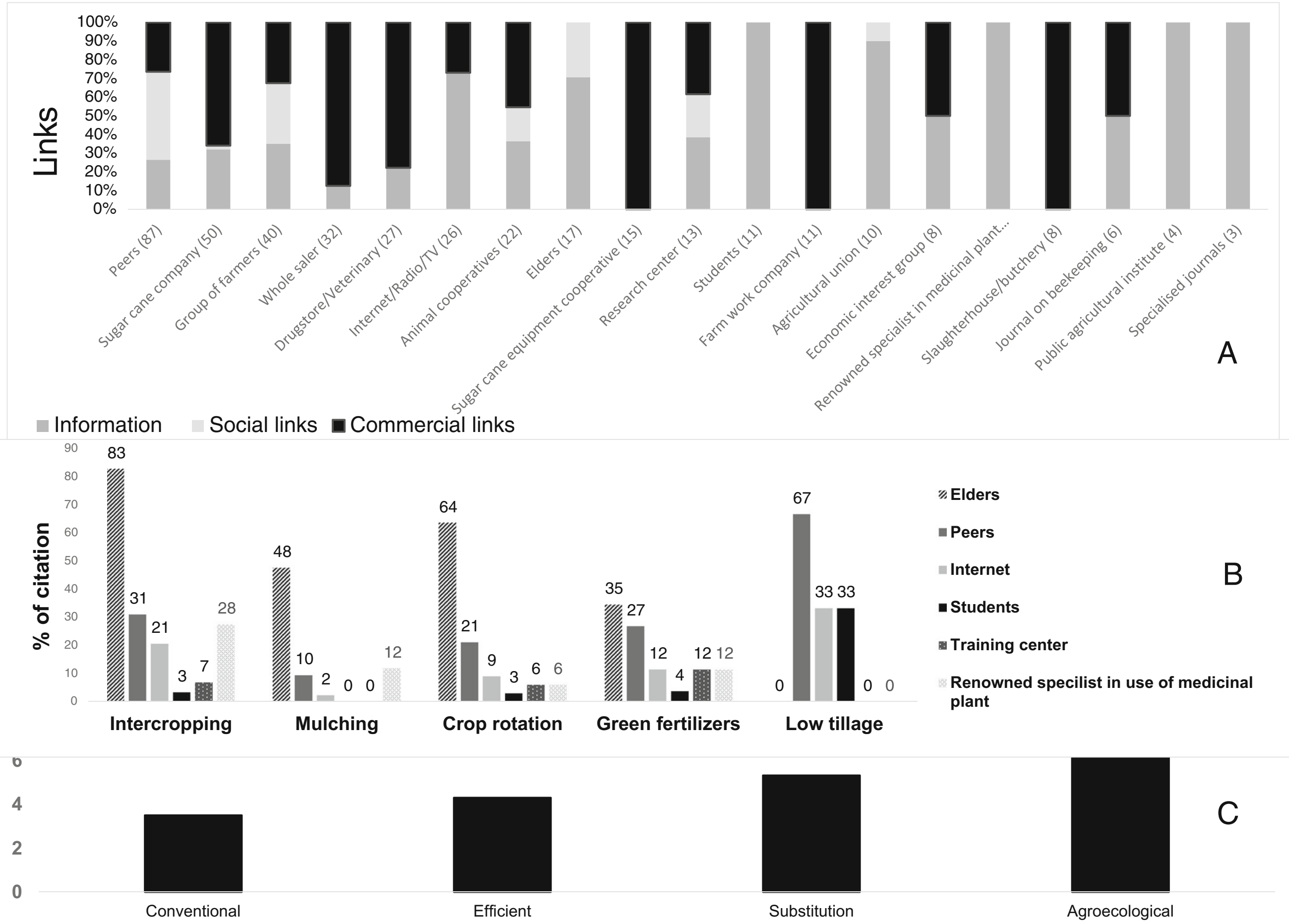

Fig. 5 Farmers' social networks promoting agroecological practices: **A** actors involved in the commercial, social, and information networks associated to agroecological practices (the total number of links per actor into brackets), **B** actors favoring the main agroecological practices, **C** average number of links per type of farmers.

mangrove swamp, dam, pond, water drilling) and their positive (such as amphibian/insect/bee refuge securing gardening production) and negative services (degradation in water quality and risk of contamination by pesticides). They then identified the actors involved in the provision and use of natural resources. Specific attention was given to the network of actors involved in the management and use of water and soil, which emerged as the two key resources for farmers. This specific step of our methodological framework allowed the identification of additional actors from those identified in step 3:

- Those who impose the rules of use (e.g., the region, department, administrative services)
- Those who play a role in land access and management (e.g., banks, lawyers, landowners, agricultural unions)
- Those who influence use by providing inputs, information or advisory support (e.g., innovative farmers, training centers, the Chamber of Agriculture)
- Those competing for the use of the resource (e.g., melon producers who have priority access to water given the importance of this value chain for exports, and who use mainly conventional practices, sugar cane producers who are increasingly installing irrigation systems, consumers, distilleries)

The lack of functional farmer groups or organizations was mentioned. In this session, participants expressed misunderstandings and feelings of mistrust between actors in the agricultural sector (*sensu largo*).

While step 3 made it possible to identify enablers for the implementation of agroecological practices, step 4 mostly highlighted constraints to their implementation. This is not surprising since, according to Anderson et al. (2019), access to natural resources is one of the main lock-ins to the wide-scale use of agroecological practices. Agroecological transformations are closely tied to food producers' need to control, use, and shape or configure soil and water. In our specific case, privatization of water by melon producers and the threat of soil and water degradation due to the chlordecone pesticide (farmers mentioned flows of potentially contaminated water from the southern part of the island in periods of water deficit) seem to provide little incentive to invest in agroecological approaches.

3.5 Action plan at the level of the territory

Working from the discussion on ecosystem (dis)services and actors, we asked participants to define a vision for their territory for the next 10 years as the basis on which to build an AET action plan. During the previous day's discussions, one farmer mentioned the need for their territory to become a "pole of agroecological experimentation." Participants quickly validated the use of this sentence and adapted it to define their vision, which was named "The Nord Grand Terre territory as a hub of experimentation and development of sustainable agriculture." They then identified the changes in behavior, practices, and interactions for different actors involved in the socio-technical and social-ecological system that would be needed to achieve this vision, the obstacles that existed, and the potential actions that different actors would need to take to overcome them (Table 2). This made it possible to locate all of the changes in an impact pathway toward AET. The resulting five key areas of change and the actions required to achieve them provide the backbone of an action plan at the territory level:

1. Building a shared vision of the territory and its complex social-ecological interactions through multi-actor forums, peer visits, and social media to improve farmers' knowledge of their natural resources. Here the demand was to avoid tensions in the use of these resources and competing actions at the territory scale, particularly for the use of water and soils as highlighted in step 4.
2. Improving collective understanding of the natural environment and the ecological processes at play in the different ecosystems. For example, farmers proposed establishing refuge areas to preserve and dynamize biodiversity; this requires training and information sessions.
3. Diversifying farming systems based on agroecological principles (cropping and livestock breeding, associated crops, agroforestry) through improved research on agroecological practices and on tools to help farmers monitor changes on their farms. Older farmers have a good knowledge of agroecological practices as highlighted in step 3, but farmers mentioned their need for support from researchers to assess the performances of such practices.
4. Improving the institutional environment to better support farmers according to their specific situations. This would include the use of European funds to strengthen their organizations and local committees made up of public (research, local administrative authorities) and private institutions (banks, etc.) to support farmers' most innovative projects. The conditionality for obtaining these funds, such as the ability to pre-finance investments that are later reimbursed, hinders access for smallholder farmers with limited financial resources.
5. Moving toward greater autonomy of the territory and the whole region. Such autonomy is a recurrent topic in Guadeloupe, which relies on imports of food and agricultural inputs. Farmers proposed an increased use of agricultural by-products to improve the autonomy of the territory in terms of fodder, organic fertilizers, and energy. They also proposed a Nord Grande Terre label that consumers could recognize.

This step helped farmers identify by themselves the complexity of changes to be implemented beyond the farm scale for an AET. Compared to the scenarios defined at the individual level (step 2), or to the constraints identified at the territory level (step 4), this step highlighted that collective reflection and design efforts generated an action plan supporting farmers' creativity and ambition, empowering them to "think big" beyond individual action. In particular, it highlighted that by using the available resources at the territory scale it was possible to find synergies between areas and actors. An important element identified by the farmers was that different actors need to better understand each other's constraints and opportunities, the functioning of the natural resources of their territory, and their own interactions. For example, flows of biomass between agriculture and the energy sector and institutional innovations such as multi-forums of actors were proposed. Some noted that, "This is the first time that we have been involved in a diagnosis and an exchange of points of view where the farmers are the ones who mainly speak." Others said, "In addition, we went a little further into identifying actions that concern us and in which research will play a role (training, joint experiments, facilitation of exchanges with other actors)."

Farmers who participated in this step mentioned that they would keep track of the concrete benefits of research projects. In studies focusing on the definition of scenarios, it is not easy to assess their concrete and futures outcomes, given that they generally aim to improve capacities to produce anticipatory knowledge and strategic planning rather than to provide ready-made solutions (Dumrongrojwatthana et al. 2011; Pissonnier et al. 2019; Vervoort et al. 2014). Furthermore, the associated change in practice may happen in the medium or long term. However, monitoring and evaluation should be an inherent part of the implementation of action research based on these plans in order to assess how much these plans inform actual action and whether the process unfolds in different ways and why.

3.6 What do we learn from applying this systemic process?

We aimed to propose an operational method to guide farmers, individually and collectively, in the definition of scenarios for an AET involving changes in farming systems, socio-technical systems, and social-ecological systems. Recently, the method

Table 2 Action plan proposed by farmers at territory scale. †Knowledge and capacity, ‡Organizational, §Technical.

Changes need for an agroecological transition	Obstacles to changes	Actions/solutions proposed	
		Type	Description of the actions
Build a shared vision between territory actors	Lack of shared vision regarding the agriculture of the future	KC†	farmers contribute to defining a structuring basis for the agriculture of the future
		KC	Break down into actions, even small ones, to start
	Lack of knowledge regarding actual agricultural conditions and farm diversity	KC	Farmers and producer organizations (POs)/associations organize forums, discussions, visits "between us" and multi-actors
		KC	Research train territory actors to help them change their ways of operating
Know and understand the natural environment	Loss of local knowledge, too much theory in agriculture training programs and not enough practice Despite their high education levels, young people implement practices harmful to the environment	KC	Farmers and other actors articulate traditional local knowledge with the use of internet technologies, farm visits
Diversify production following the principles of agroecology	Farmers are unfamiliar with innovative practices Holding a second job reduces time available for farming and to reflect and build collectively with other farmers	O‡	The government and the Chamber of Agriculture deploy more technicians in the field
	Lack of producer associations/organizations Competition from imported products and lack of political will to reduce this	O	Farmers create farmer groups producing food crops for the local market: planning supply, support direct sales, search for subsidies, shared equipment
	Limited access to credit for subsistence crops	O	The government reviews cross-compliance requirements for agri-environment-climate measures (AECM)
	Land often steered toward large producers and for export crops	O	Research supports farmers in maintaining sugar cane at the head of the rotation to keep soil healthy and develop associated livestock farming
	Agricultural practices: eradicating pests rather than managing them, limited knowledge on alternatives to the use of fertilizers, and poor control of parasites and diseases	O	Research groups and technical services help in the design, assessment and dissemination of agroecological practices (information, training programs, spaces for sharing)
		T§	Research develop tools that help farmers to carry out their own diagnoses (water and soil)
		T	Farmers establish refuge areas to preserve and dynamize biodiversity
		T	Research efforts focus more on biocides for crops and livestock
		T	Farmers, engine manufacturers (machinery sharing cooperatives (CUMA), agricultural contractors) reduce/adapt tillage depth and equipment size
		T	Farmers with the support of advisory services produce local feed with high protein content for livestock
Improve the institutional environment: support-advisory structures better taking into account actual local conditions and accompanying farmers in the agroecological transition	POs, CUMAs, and service providers poorly adapted to local conditions and favor large production and distribution structures	O	Local policy makers support producers so that they create functional organizations and mobilize funding from the second pillar of the European common agricultural policy (EAFRD)
	Most farmers poorly informed about their rights and opportunities (subsidies)	O	Need greater commitment from farmers

Table 2 (continued)

Changes need for an agroecological transition	Obstacles to changes	Actions/solutions proposed	
		Type	Description of the actions
	Few investors, no bank support for innovation projects	O	More frequent contact between farmers and the Chamber of Agriculture
		O	Farmers and other actors set up committees to validate projects useful to all
		O	The government and the private sector develop agro-processing units
The territory, or even the island, achieves autonomy	Low purchase prices of agricultural goods	O	The government, private sector, and region develop new outlets for agriculture such as energy-producing crops, protein-rich livestock feed, etc.
	Lack of local market outlets for agricultural production	O	Farmers and other actors develop and "NGT origin" label that consumers can recognize
	Insufficient valorization of agricultural by-products	T	Farmers develop the use of by-products for fertilization

proposed by Della Rossa et al. (2022) allows the assessment of lock-ins to the adoption of previous agroecological innovations and to define and explore alternative territory innovations. The method we propose allows both the diagnosis at the individual (step 1) and territory scale (steps 3 and 4) and the exploration of individual (step 2) and territory alternatives (step 5), with the aim to identify key technical, practice, organizational, and interaction changes needed for an AET. Our modeling tool at the farm scale allowed farmers to explore potential and realistic combinations of changes at the individual level. Depending on the location of farms in an AET gradient, various scenarios emerged. At the territory scale, the scenario exploration was based on future narratives rather than on modeling in order to be able to consider the complex socio-technical or social-ecological changes without the feasibility constraints of models. Indeed, the building blocks of the action plan developed included both changes in the socio-technical systems (e.g., new role for research scientists and change of interactions between actors) and the social-ecological systems (e.g., refuge areas to preserve and dynamize biodiversity). Having been developed within a research project, these building blocks also served to identify key intervention areas for researchers by enabling a better understanding of the role of different actors and interactions in the socio-technical and social-ecological systems in which they operate.

In order to follow up on the research-supported interventions, we monitored the first outcomes of applying our methodological framework in the action research project that followed the scenario and planning workshop (ten scientists from this project participated in steps 4 and 5). The project partially drew on these results as it was already funded with defined activities. Specifically, the research team better identified their own role in a broader innovation ecosystem (Pigford et al. 2018) and their potential role as facilitators of interactions between the various stakeholders in the territory. They organized three successive focus groups: one with the farmers who participated in the scenario and action plan definition, another with the scientists involved in the project, and a last one with farmers, scientists and stakeholders identified in the action plan (representatives of local decision-makers, melon farmers organizations, chamber of agriculture, advisory services). During these focus groups, they identified the concrete actions that they would specifically develop. One of these concrete actions was the implementation of on-farm experiments on organic poultry and associated fodder legume production involving eight farmers who participated in the scenario and action plan definition. As animal concentrates are imported in the region, local production of legumes to feed animals needs to be in place in order to develop organic poultry based on agroecological principles. The aim of the on-farm experiments was to both build technical references and promote interactions between farmers interested in poultry production and those interested in legume production, and support medium-term involvement of new farmers in the development of this new value chain (INRAE 2021a). For scientists, this implies a drastic change in their main mode of experimentation, which was mostly conducted on-station (INRAE 2021b). Such a change is not easy, and requires a change in researchers' attitudes toward participation, local stakeholders (Neef and Neubert 2011), the type of methods used, and the type of knowledge produced. As shown in Barnaud et al. (2018), methods like the one we presented not only create awareness of mutual interdependencies between people and the ecological processes that shape their activities, but are also key for researchers' reflexivity on their role in the action arena. For the stakeholders, who were not involved in the initial definition of the action plan, there was considerable enthusiasm about the participatory process, but this was not accompanied by concrete ideas as to what they wished to implement.

In this type of collective, forward-looking co-design, it is critical to acknowledge in a transparent way that the choices made are not value-free (as they seldom are). The action plan built by participants reflects the values, perceptions, and views deliberated, negotiated, and agreed upon by that group. Who participates in defining the desired changes and the strategies to achieve them is not a neutral question, and the facilitator of such a collective process needs to be vigilant about detecting eventual power imbalances and implement solutions to mitigate them (reshuffling group participants, splitting groups, balancing between collective discussion and individual reflection, and so on). The experimental setting of our application and our interest in tackling potential power dynamics between actors in this territory justified our choice of piloting the method with smallholders. Acknowledging and addressing power and information imbalances, along with considering the heterogeneity of targeted populations, is crucial for the design of research and development interventions that sustainably improve livelihoods through their embeddedness in local contexts (Blundo-Canto et al. 2018b). However, our choice represents a constraint in terms of representativeness and in understanding the perspectives and constraints of other actors whose key role was acknowledged by the farmers. In order to improve the ownership of the action plan by these actors, future applications of the method could include iterations of the method (at least for steps 4 and 5) with some of these key actors to analyze the systems and develop an action plan from their points of view. Simultaneous or sequential phases in which the action plan is built with the participation of different actors during the same workshop(s) or through different workshops organized by actor-type could be devised. The results would then be discussed at subsequent events in which all actors involved discuss the trade-offs and synergies between the action plans that had been developed separately and draw up a final joint action plan. Such participatory approaches need to balance legitimacy, credibility, and divergent demands (McBride et al. 2017), but also offer new interactions and mediation opportunities (Andreotti et al. 2020).

These developments would also be in line with more transboundary, inter-sectoral conceptualizations of agricultural innovation systems as agricultural innovation ecosystems supporting sustainability transitions (Pigford et al. 2018).

4 Conclusion

The application of a five-step method to describe and explore scenarios in farming, socio-technical, and social-ecological systems in the northern part of Guadeloupe with smallholder family farmers who have limited access to support services showed that each step of the method permits specific insights. At the farm scale, it was possible to focus on technical changes, which depend on the location of the farm in an AET pathway, and which mostly aim to improve the efficiency of synthetic input use or to replace synthetic inputs with organic ones. At the level of the territory, the analysis allowed us to highlight the links between farms, natural resources, and various stakeholders. It particularly highlighted the actors enabling or constraining the AET, and allowed farmers to explore more ambitious transformative changes, such as flows of biomass between the agriculture and energy sectors, and institutional innovations allowing synergies between actors. Furthermore, it showed the specific role of research scientists in a broader innovation ecosystem where other actors need to be involved, and helped the scientists involved to fine tune their research activities to farmers' needs. One of the main outcomes of the process is that it allowed a shift in the approach of researchers from experiments conducted on-station toward experiments managed by farmers, and to engage as facilitators of the interactions around the AET between stakeholders of the territory, representing a radical change of scientific attitudes. From the farmers' perspective, the process generated a new dynamic of interaction with scientists and a pilot project to develop organic poultry and fodder production, which is a challenge in the region. Future applications could include defining with participants of the process how to handle additional actions proposed in the action plan, detailing the roles and responsibilities of different actors beyond the researchers and farmers themselves. Priority could be given to defining how to support local policy makers in developing policies that would better consider the specific characteristics of smallholder farmers and facilitate the redesign of farming systems to achieve a contextually appropriate AET.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval The study was approved by the CIRAD research ethics committee; we certify that the study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Consent to participate Verbal informed consent was obtained prior to the interview.

Consent for publication The authors affirm that human research participants provided informed consent for publication of the image in Fig. 1.

Conflict of interest The authors declare no competing interests.

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